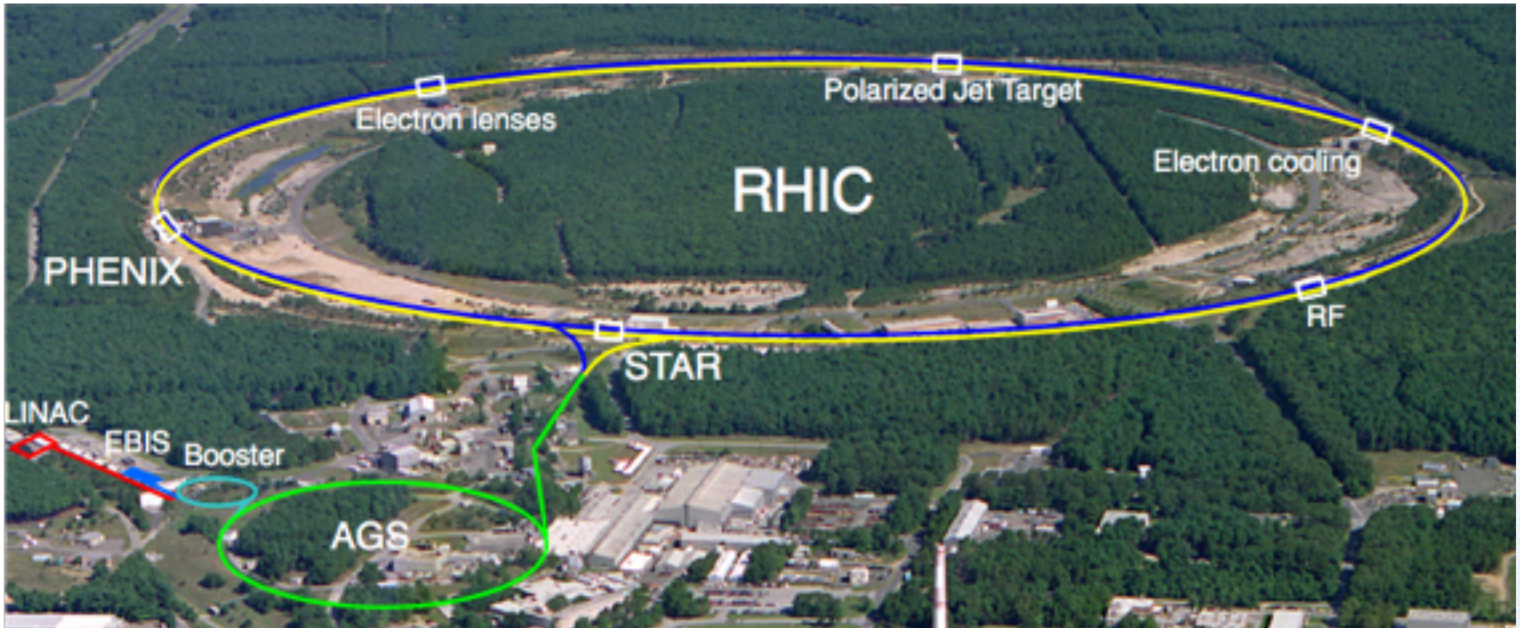
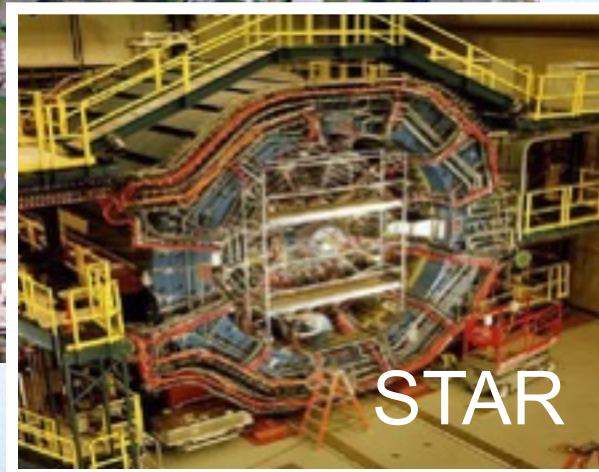
RHIC S&T Overview 2016

Berndt Mueller





Exploring the Phases of Nuclear Matter

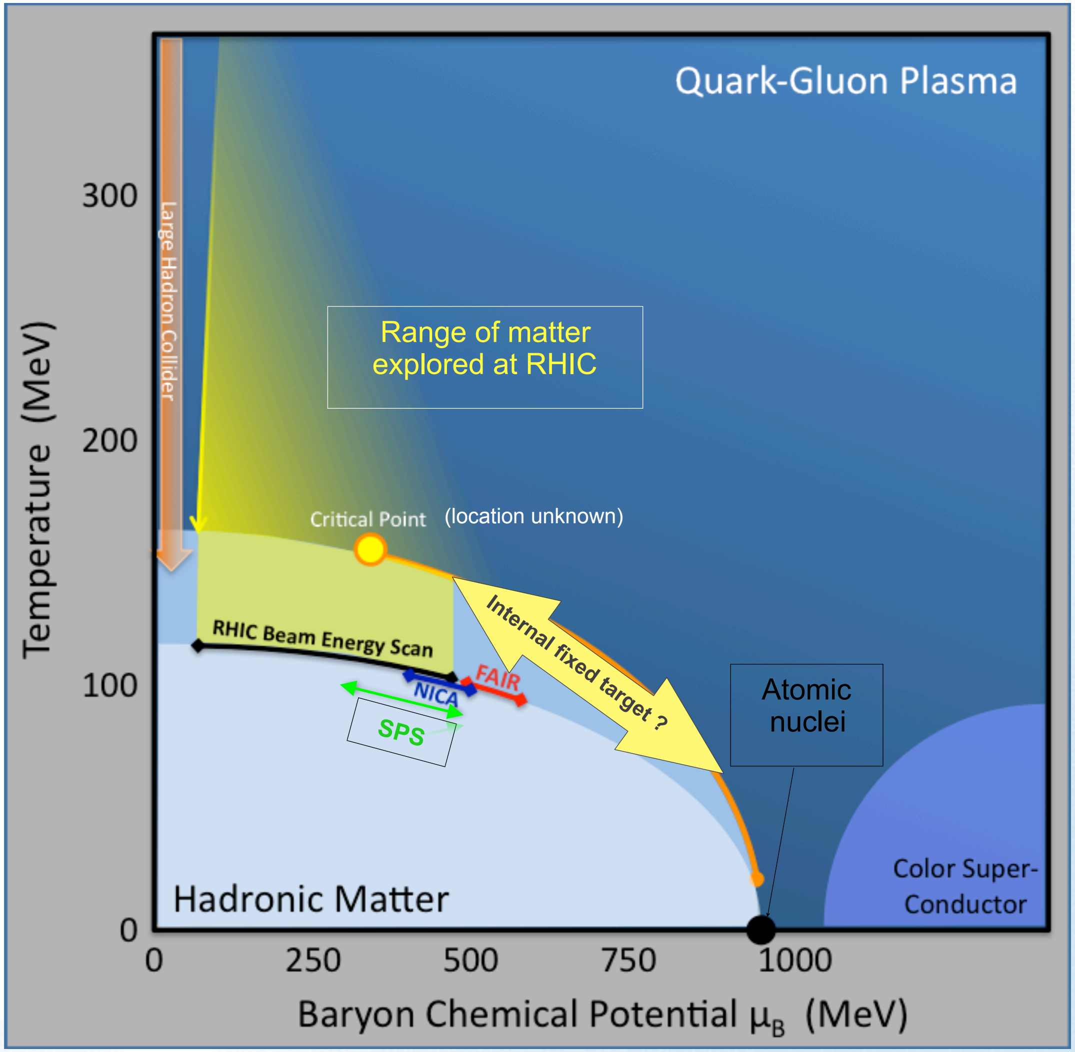
RHIC is ideally suited to explore the quark-gluon plasma (QGP) and map the QCD matter phase diagram.

RHIC has defined a multi-year program to complete its scientific mission. We just completed Year 3.

Major components of this program are:

- *Search for a possible critical point in the QCD phase diagram*
- *Find unambiguous evidence for the restoration of chiral symmetry*
- *Discover novel phenomena caused by topological QGP excitations*
- *Unravel the mechanism causing the near "perfect" fluidity of the QGP discovered at RHIC*

In addition, RHIC is the first and only polarized proton collider in the world. It is uniquely positioned to elucidate the dynamics of spin in QCD. RHIC has already discovered that gluons make up part of the spin of the proton.



2015 NSAC Long Range Plan

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *Complete the CEBAF 12 GeV upgrade and execute its program*
- *Complete construction of FRIB at MSU*
- *Run a targeted program in neutrinos and fundamental symmetries*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

Agenda of this presentation:

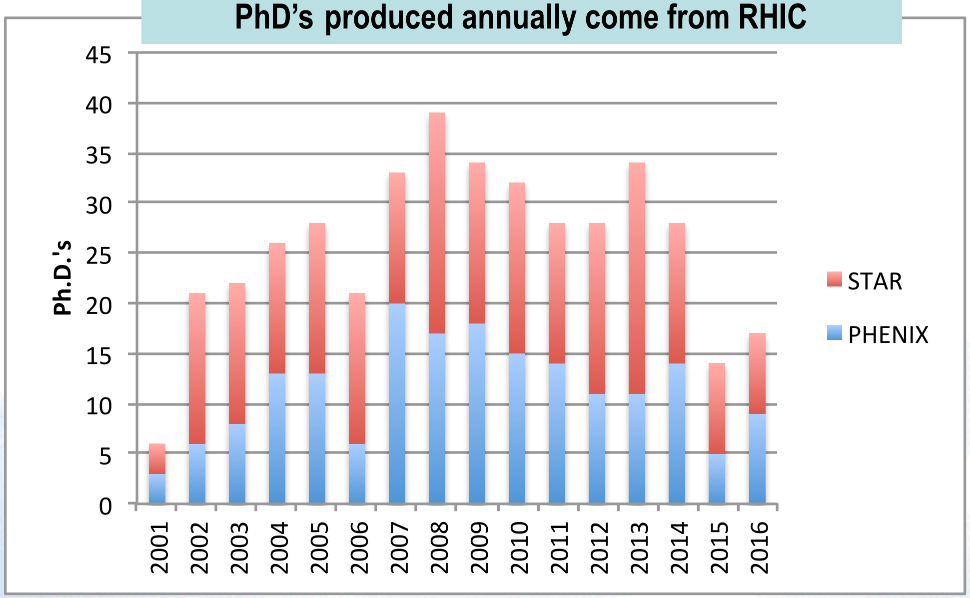
- **Recent (Run 14-16) highlights**
- **Plans for 2017-20 RHIC Runs**
- **Status of iTPC, LEReC, sPHENIX upgrades**
- **Long-term vision & transition to eRHIC**
- **Laboratory support**
- **Synergies with non-NP programs**
- **Response to 2014 recommendations**

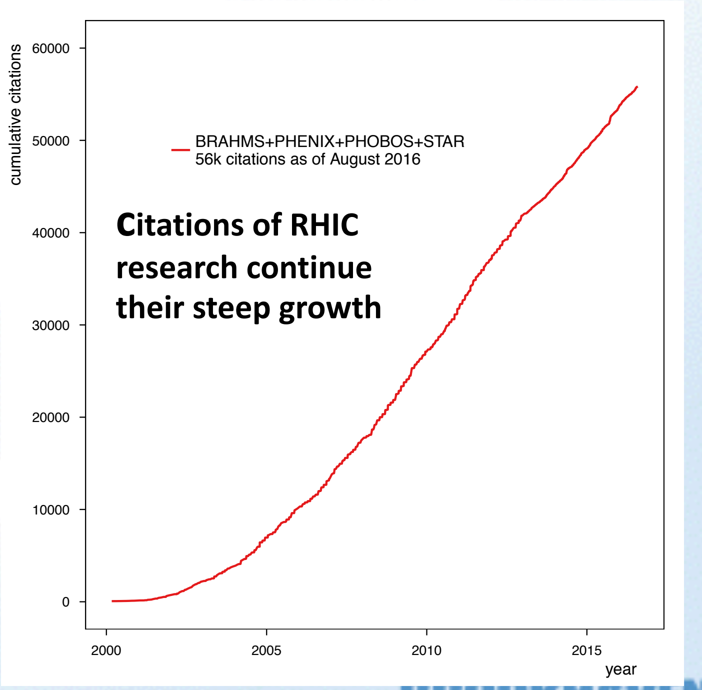
Recent Highlights

RHIC: Productivity and Impact

Collaboration	Total # Refereed Papers	Total # Citations for Ref'd Papers	# PRL's	# Citations for 2005 White Paper	Position Among Most Cited NP Papers 2001-14	# Papers with >250 Citations
PHENIX	163	~22,000	69	2,209	4	23
STAR	191	~23,000	72	2,351	3	22
PHOBOS	39	~5,000	15	1,720	5	5
BRAHMS	22	~3,500	10	1,687	6	3
Total	**415**	**~53,500**	**166**	**7,967**	**4 in top 10**	**53**

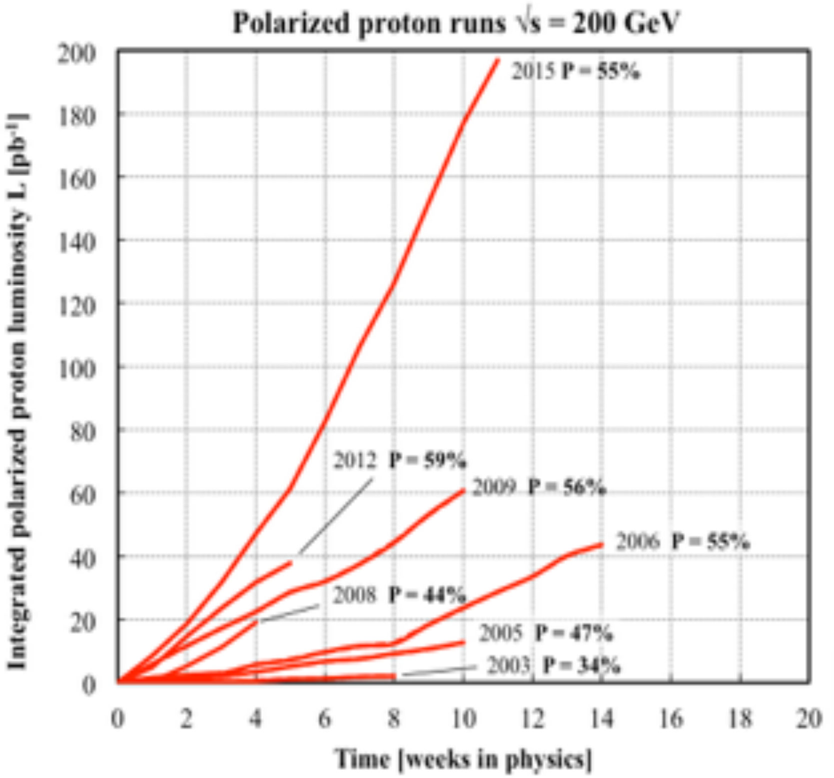
Traditionally, 40% of experimental nuclear physics PhD's produced annually come from RHIC



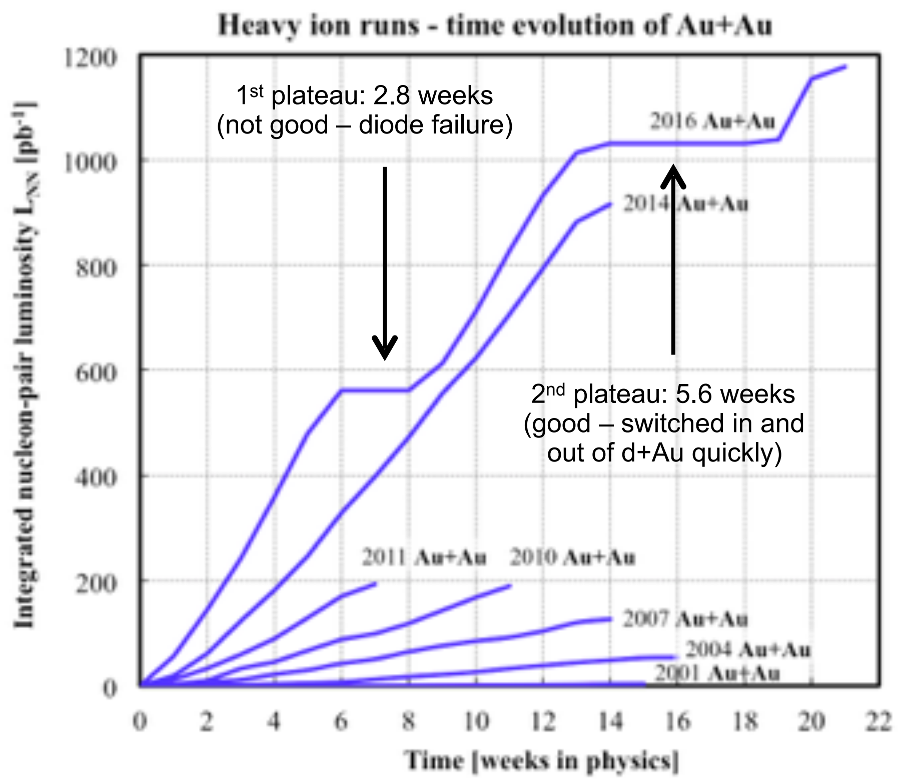


RHIC sets new records …

Run-15 integrated luminosity at $\sqrt{s}$ = 200 GeV exceeds sum of all previous runs

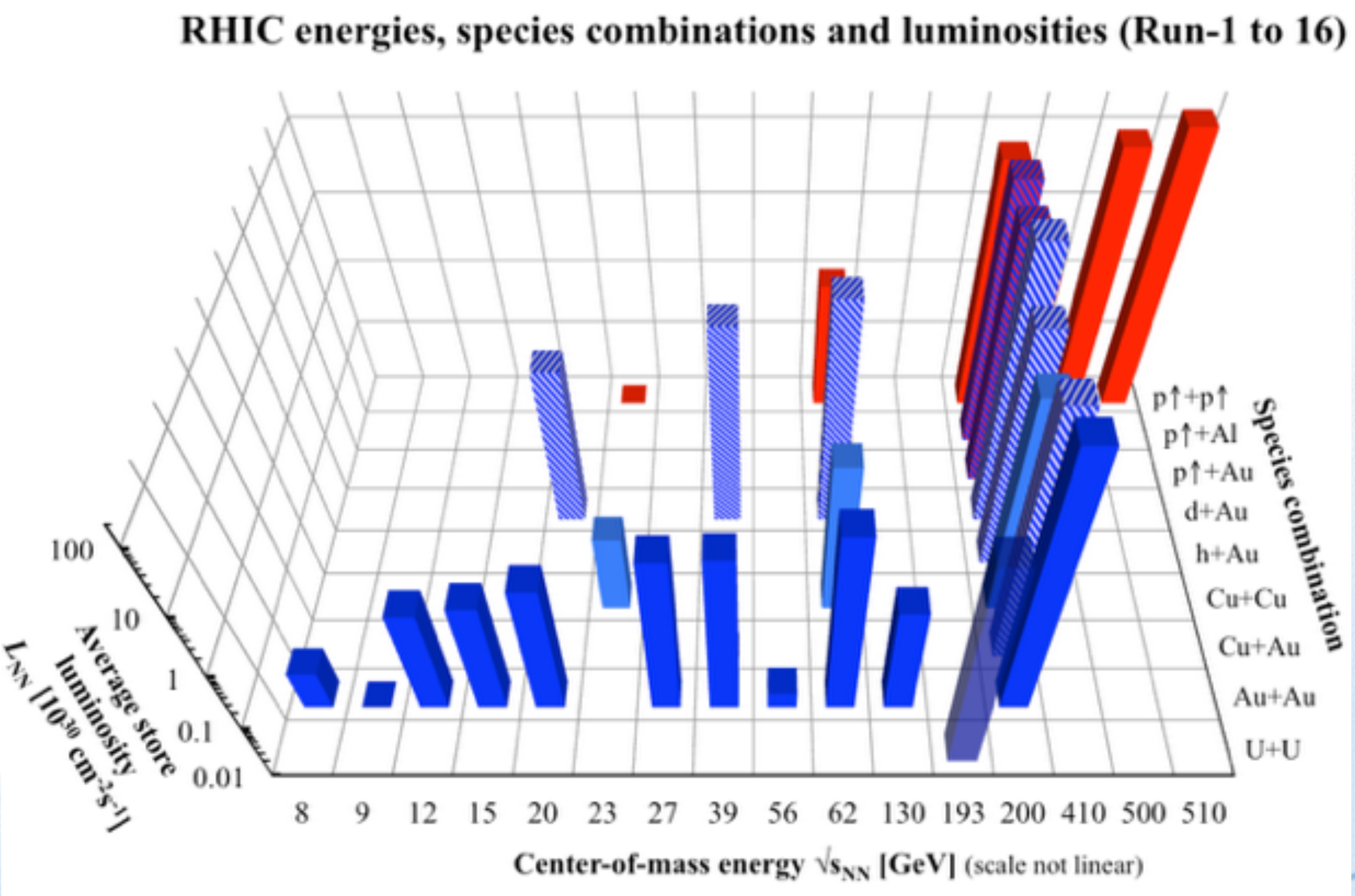


Run-16 luminosity +33% vs. 2014



d+Au reached same number of collisions in 1 week as 2008 run in 8 weeks

If science demands it, RHIC can deliver it!



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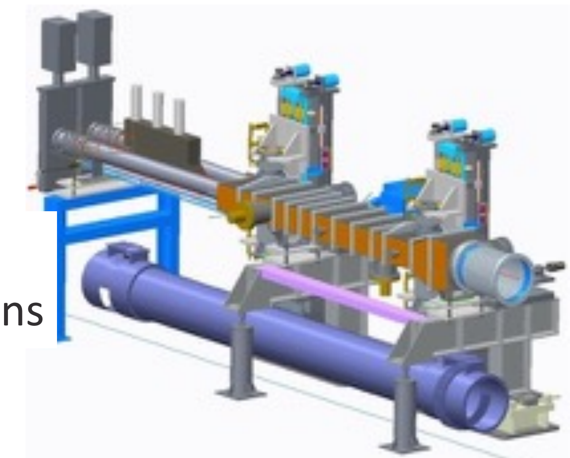
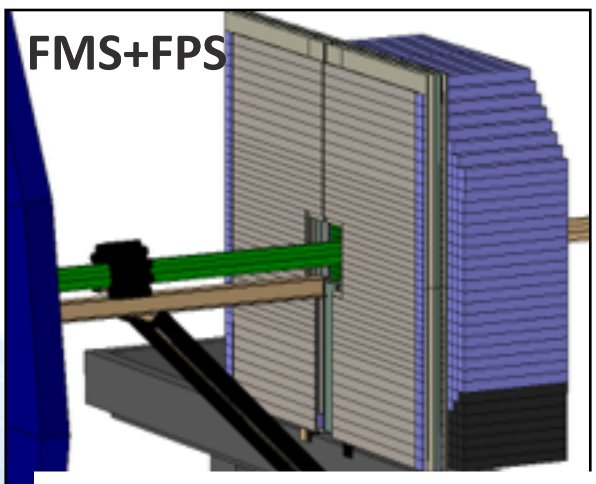
Recent Detector Upgrades

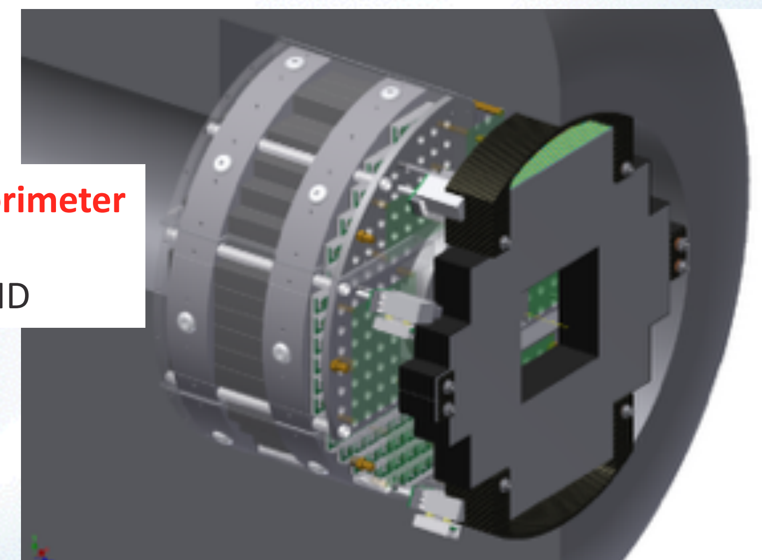
Trigger/DAQ x2 throughput



Roman Pots (2015)
Tag diffractive protons



Muon Piston Calorimeter Extension (2015)
Forward photons ID



STAR FMS + pre-shower (2015)
A_N photon, jets, Drell-Yan; ridge, fluctuation, spectators

RHIC related awards (2015-16)

- Ernest O. Lawrence Award:
  - Mei Bai (2015)
- APS Bonner Prize:
  - M. Gyulassy & H. Wieman (2015)
- APS Feshbach Prize:
  - L. McLerran (2015)
- BNL S&T Award:
  - F. Videbaek (2015), M. Okamura (2016)
- ATLAS Thesis Award, Blavatnik Award Finalist, Lee Grodzins Award
  - Dennis Perepelitsa (2015)
- Excellence Professor (U Heidelberg)
  - Raju Venugopalan (2015/16)

Mei Bai

Recent RHIC Runs

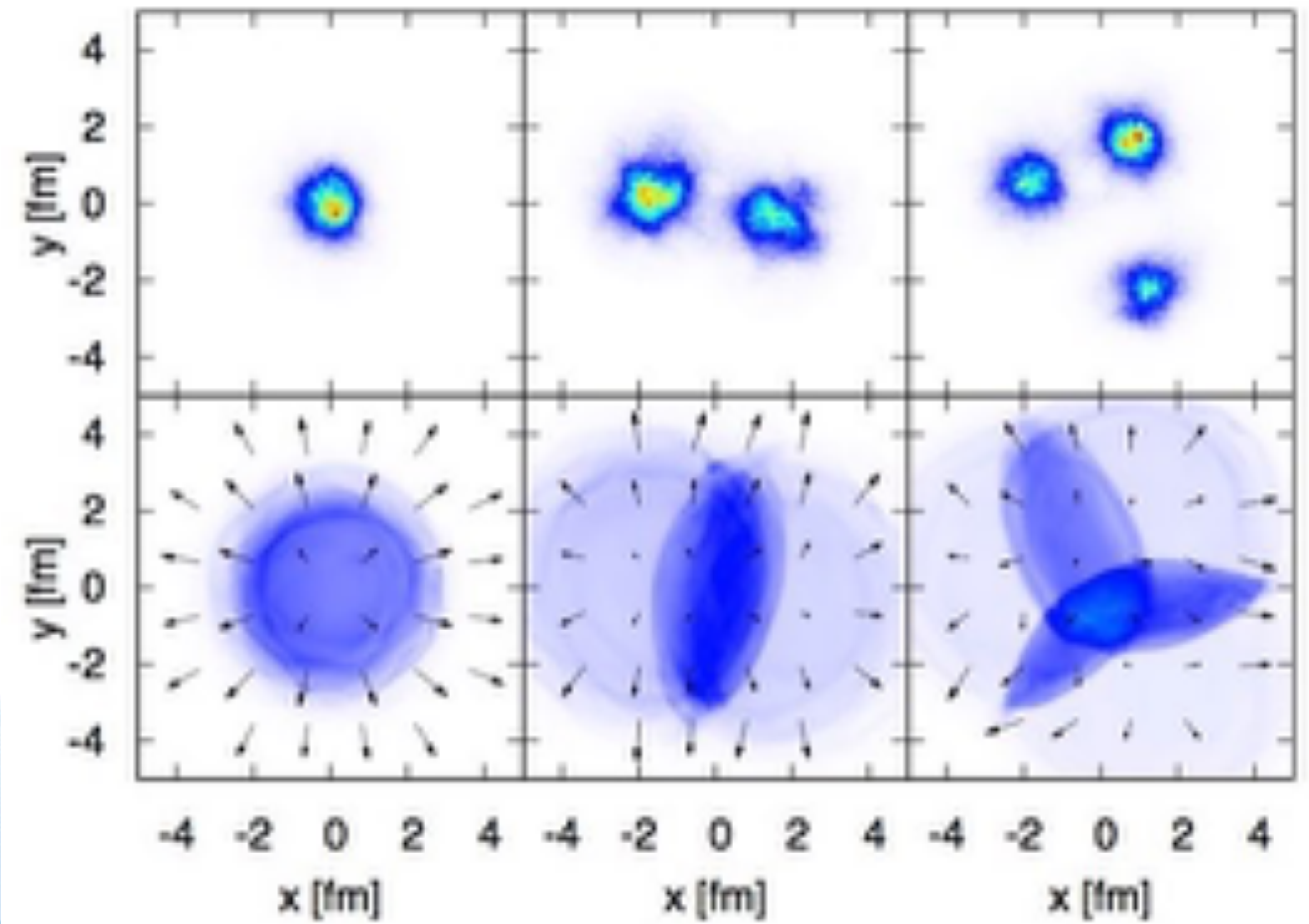
Run-15

- Transverse polarized p+p at 200 GeV, 11 weeks
- Successful operation of e-lenses
- p+Au at 200 GeV, 8 weeks
- p+Al at 200 GeV, 2 weeks
- First p+A run ever used ability to move DX magnets

Run-16

- Au+Au at 200 GeV, 10 weeks
- 56 MHz SRF, further increase in bunch intensity
- d+Au at 200, 62, 39, 19.6 GeV/nucleon, 5 weeks
- PHENIX / STAR detector protection task force report

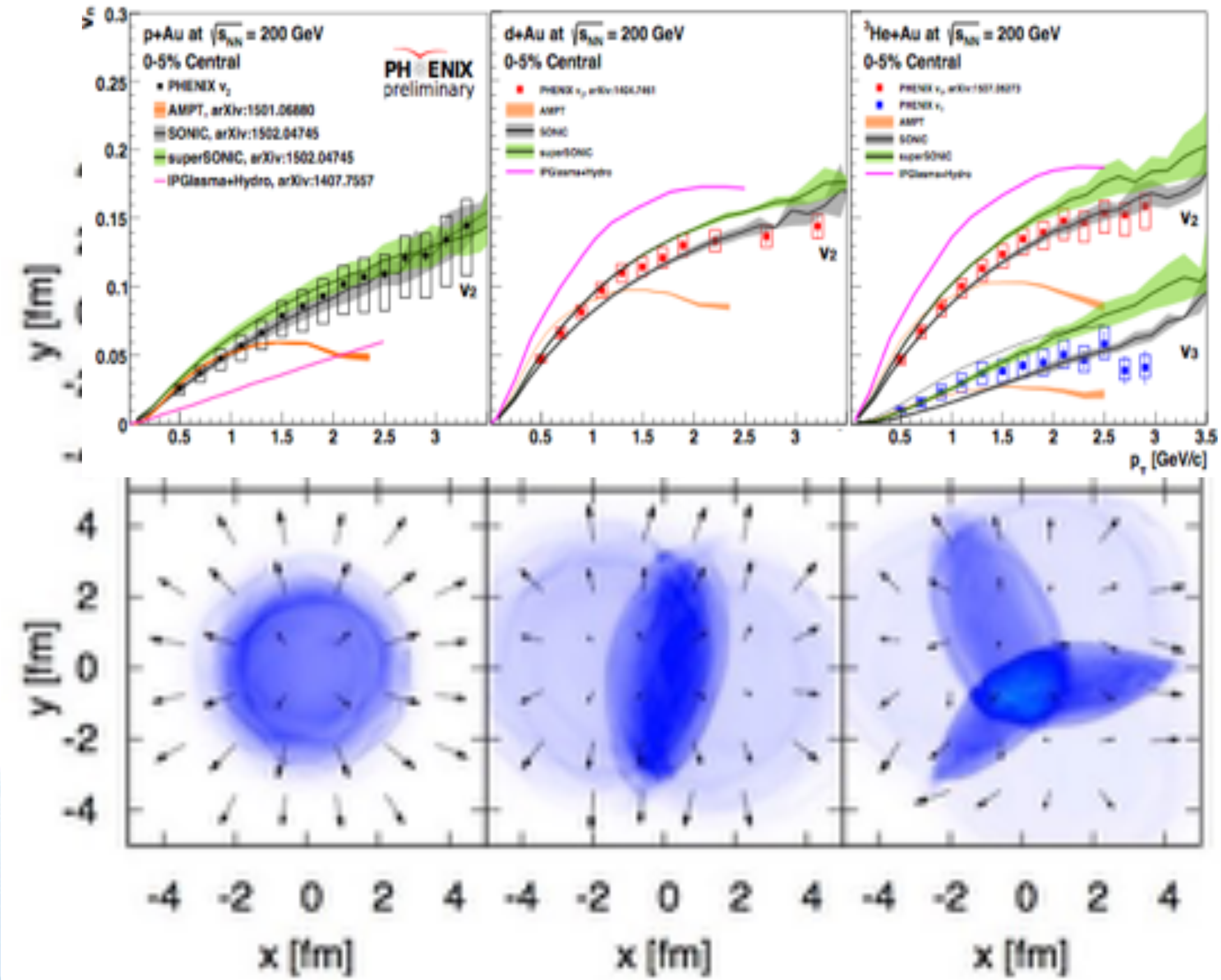
Tiny drops of QGP?



Initial state

Final state

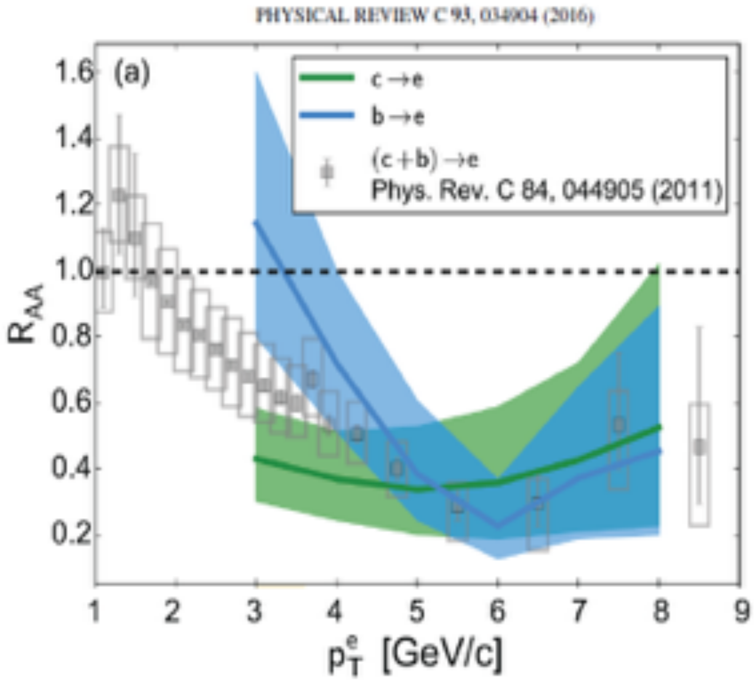
Tiny drops of QGP?



Data-Theory comparison confirms hydrodynamic collective flow

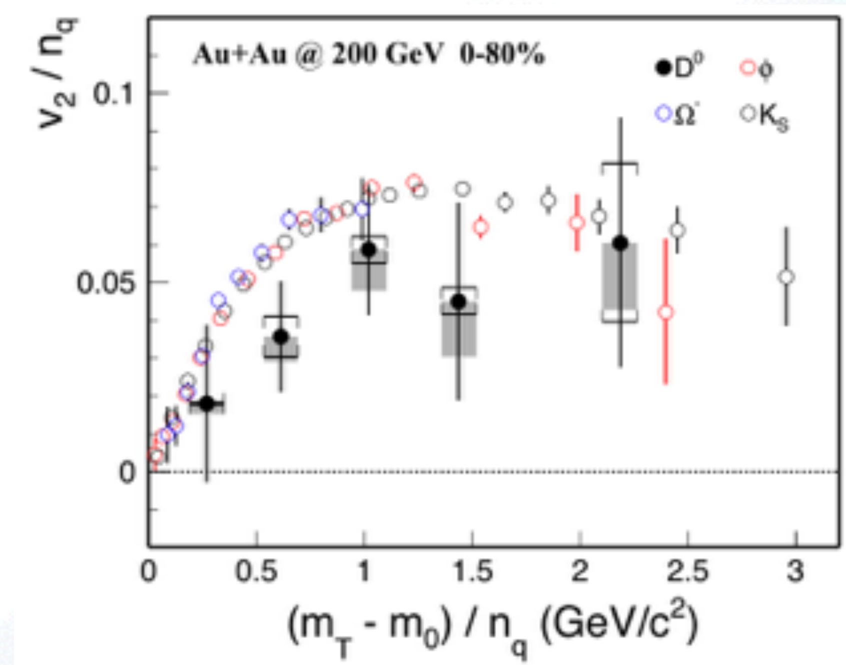
Final state

Heavy Quark Transport in the QGP



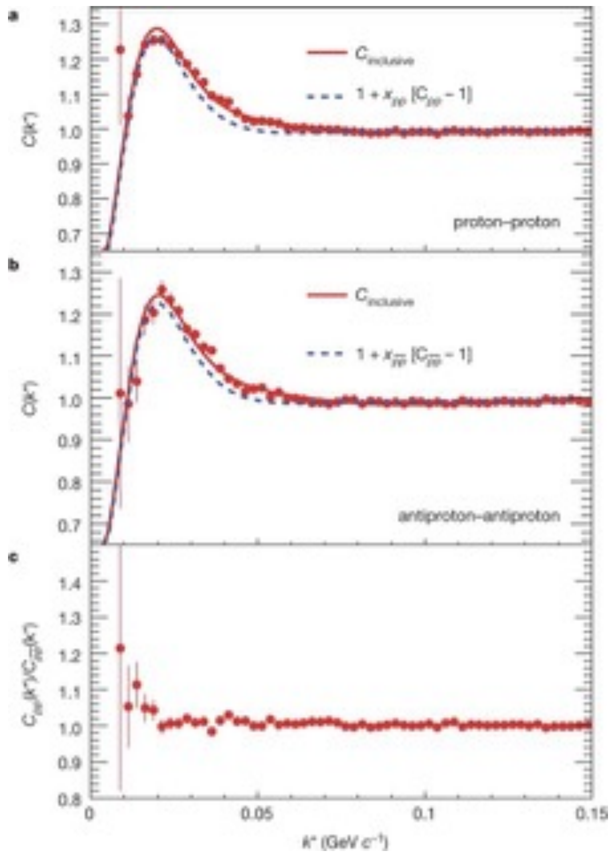
Both b and c quarks are suppressed at large p_T

Hadrons containing c quarks show signs of collective flow



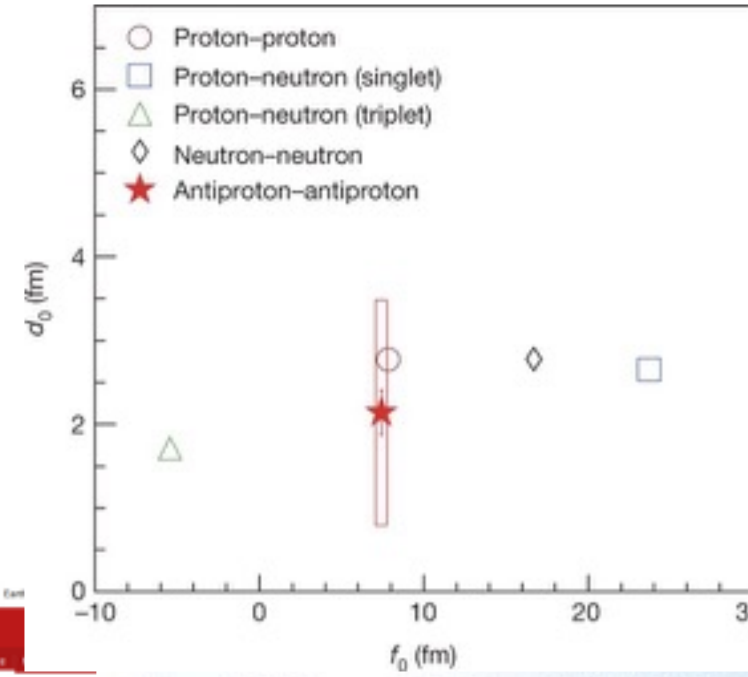
Small heavy quark diffusion constant confirms strong coupling of QGP at different scale from hydrodynamics.

Interaction between two antiprotons



[Nature **527**, 345 (2015)]

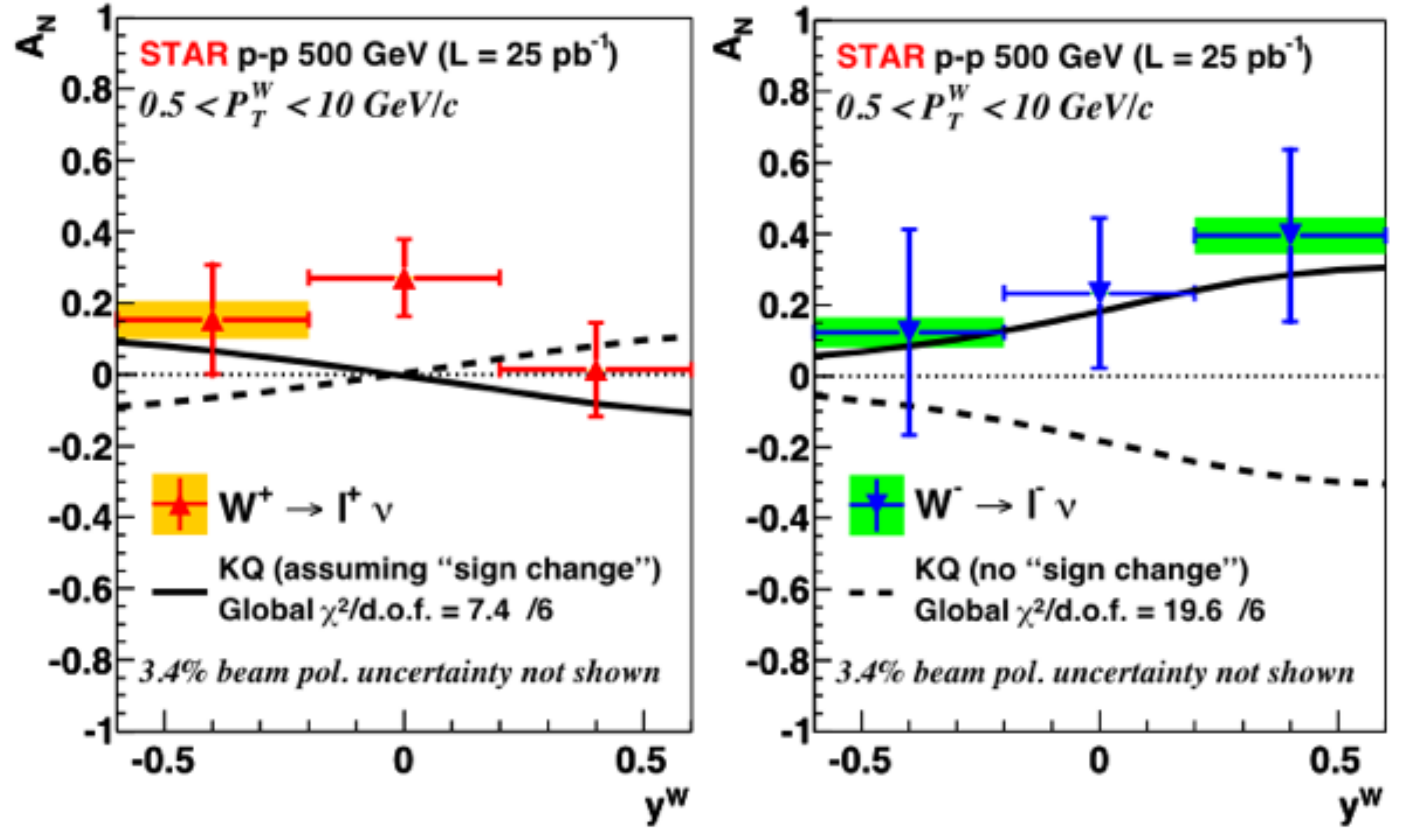
By applying a technique similar to Hanbury-Brown and Twiss intensity interferometry, we show that the force between two antiprotons is attractive.



We report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction

W Sivers function

Phys. Rev. Lett. 116 (2016) 132301



Chiral Magnetic wave

Editors' Suggestion

Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions

L. Adamczyk *et al.* (STAR Collaboration)

Phys. Rev. Lett. **114**, 252302 (2015) – Published 26 June 2015

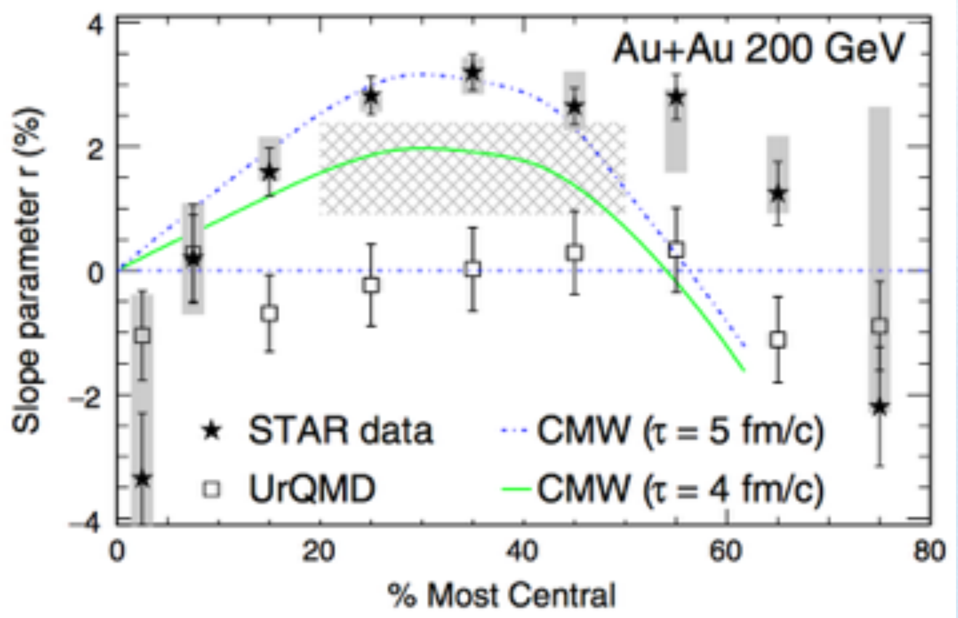
A possible signature of chiral symmetry restoration, in the form of a chiral magnetic wave in the quark-gluon plasma, has been observed in heavy-ion collisions at RHIC.

Show Abstract +

CMW = Coupled density waves of electric and chiral charges

$$\vec{J}_{em} = \frac{N_c e^2}{2\pi^2}\mu_5 \vec{B}$$

$$\vec{J}_5 = \frac{N_c e}{2\pi^2}\mu_q \vec{B}$$



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Future Science 2017-20

Run-17 Plan

- High luminosity 510 GeV transverse polarized p+p run (13 weeks)
- Study scale evolution of the Sivers effect in W-boson production; possibly confirm sign change of the Sivers effect relative to DIS

- Proof of Principle test of Coherent electron Cooling (2 weeks)

Run-18 Plan

- Isobar system (^{96}Ru - ^{96}Zr) run at 200 GeV (8 weeks)
- Critical signature of Chiral Magnetic Effect
- Au+Au run at 27 GeV (2 weeks?)
- Energy dependence of CME

Strongly endorsed by 2016 RHIC PAC.

Transverse polarized p+p collisions

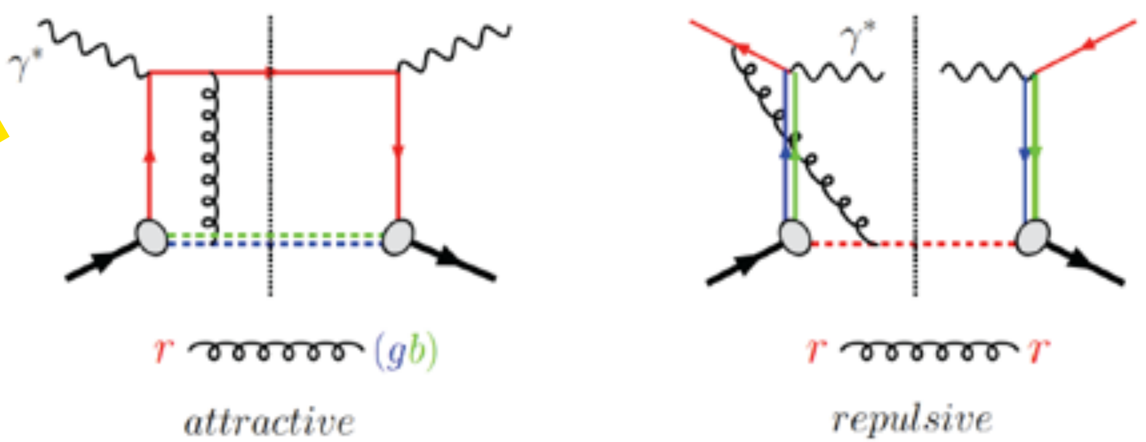
Access the dynamic structure of protons:

→ Test and confirm QCD structure of color spin interactions
  → Non-universality of transverse momentum dependent functions
  → $\text{Sivers}_{DIS} = - \text{Sivers}_{pp}$
    → Observable: A_N for Drell-Yan and $W^{+/-}$ production

Will achieve NP Performance Milestone HP13 in Run 17

DIS:
γq-scattering attractive

pp:
qqbar-anhilation repulsive

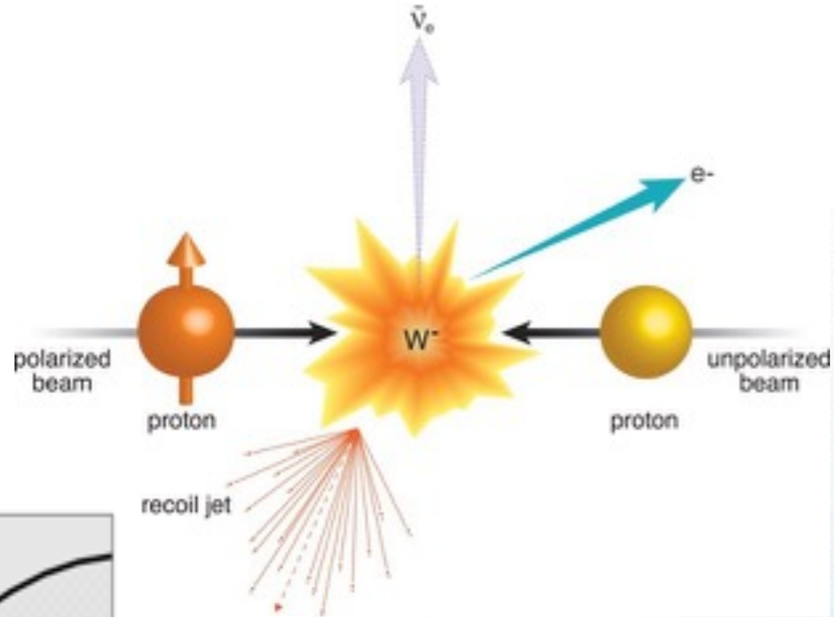


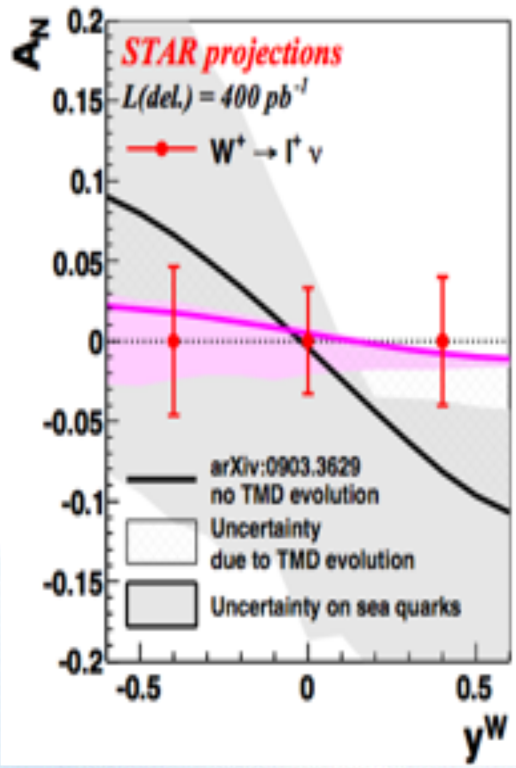
→ Test scale evolution of transverse momentum dependent functions
  → Observable: compare magnitude of A_N for Drell-Yan and $W^{+/-}$

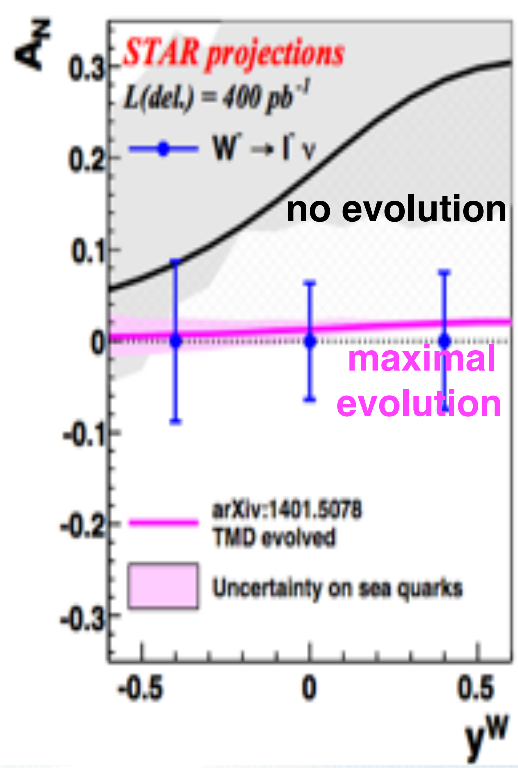
Scale: DY: $Q^2 \sim 16\ GeV^2$ $W^{+/-}$: $Q^2 \sim 6400\ GeV^2$

W Sivers function

Analysis of Run-15 data demonstrates viability of definitive measurement







Projections for Run-17

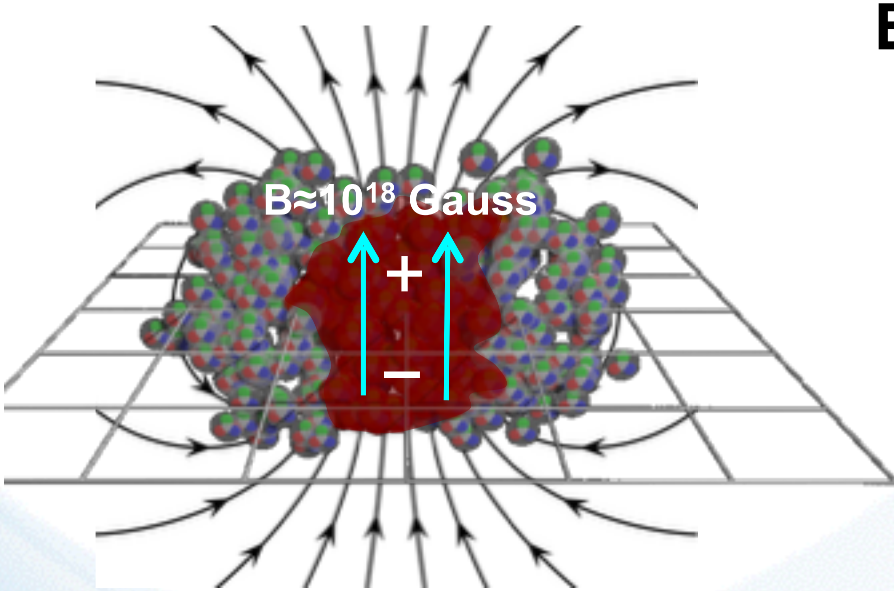
TMD scale evolution assumptions testable. Critical input into projections for EIC !

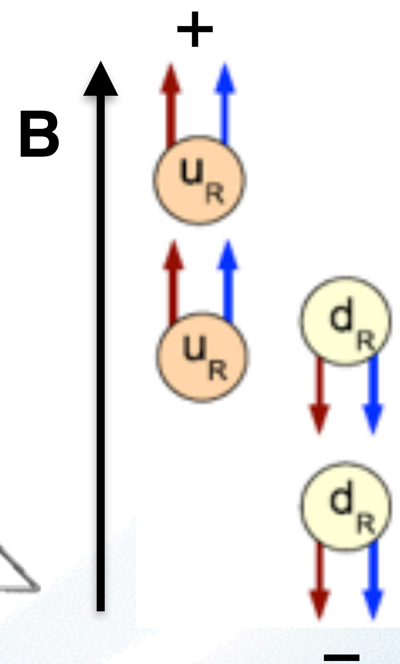
Anomalous Currents probe Chiral Symmetry

The chiral anomaly of QCD creates fluctuating differences in the number of left and right handed quarks, characterized by a chiral chemical potential μ_5.

In a chirally symmetric QGP, this imbalance generates an electric current along the magnetic field (chiral magnetic effect).

electric charge separation





Spin

Momentum

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5\ \vec{B}$$

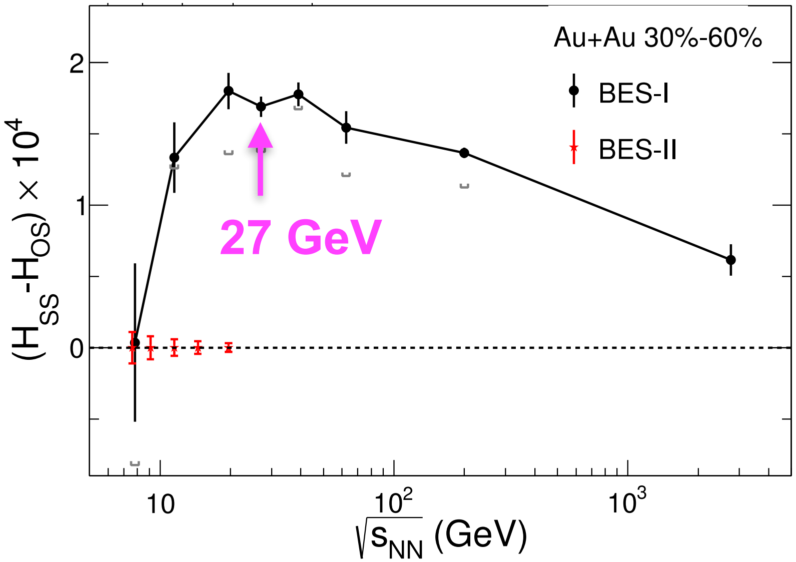
$$\langle \mu_5^2 \rangle \neq 0$$

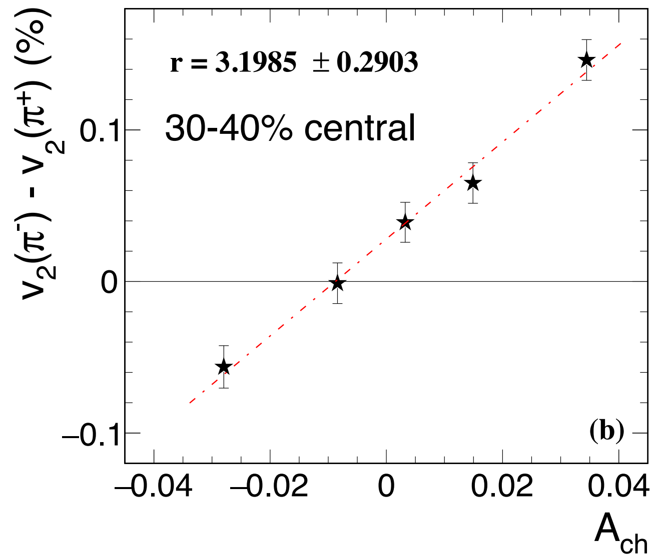
$$\langle JJ \rangle \neq 0$$

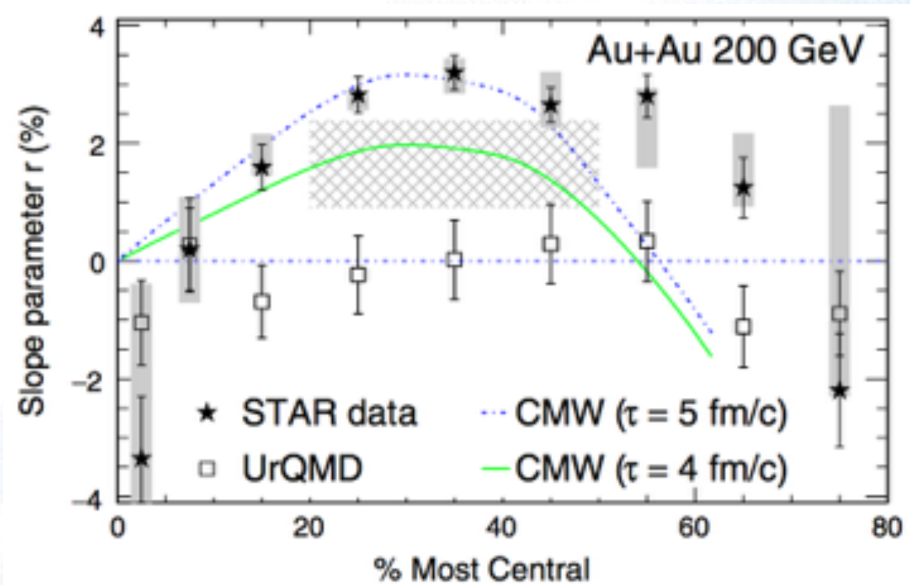
$\boxed{\mu_5 > 0}$

CME Phenomena

…were observed at all but the lowest energy





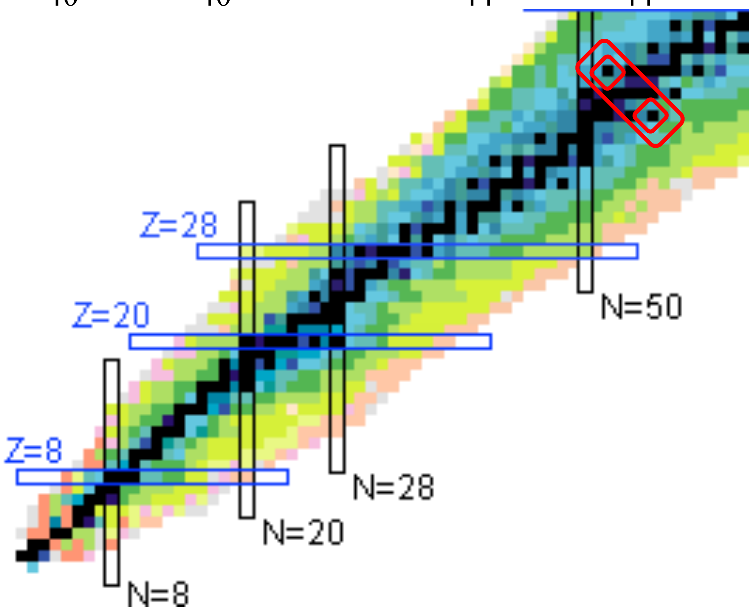


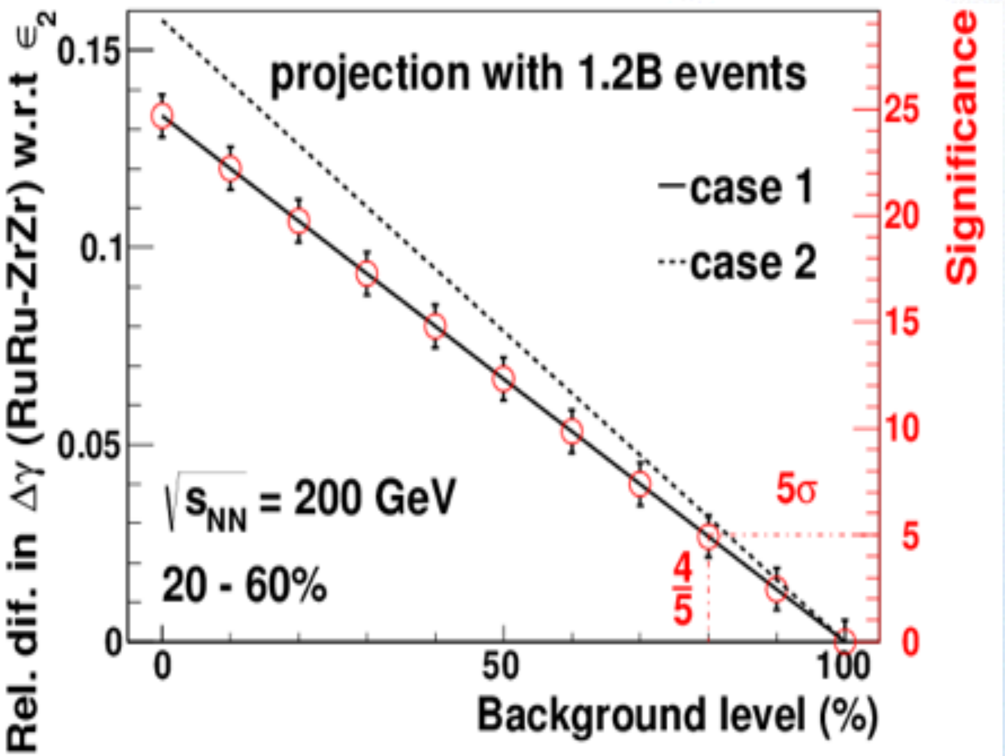
But models with magnetic field-independent flow backgrounds can also be tuned to reproduce some of the observed charge separation effects.

Isobar comparison run (Run-18)

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$^{96}_{40}Zr + ^{96}_{40}Zr$ vs. $^{96}_{44}Ru + ^{96}_{44}Ru$

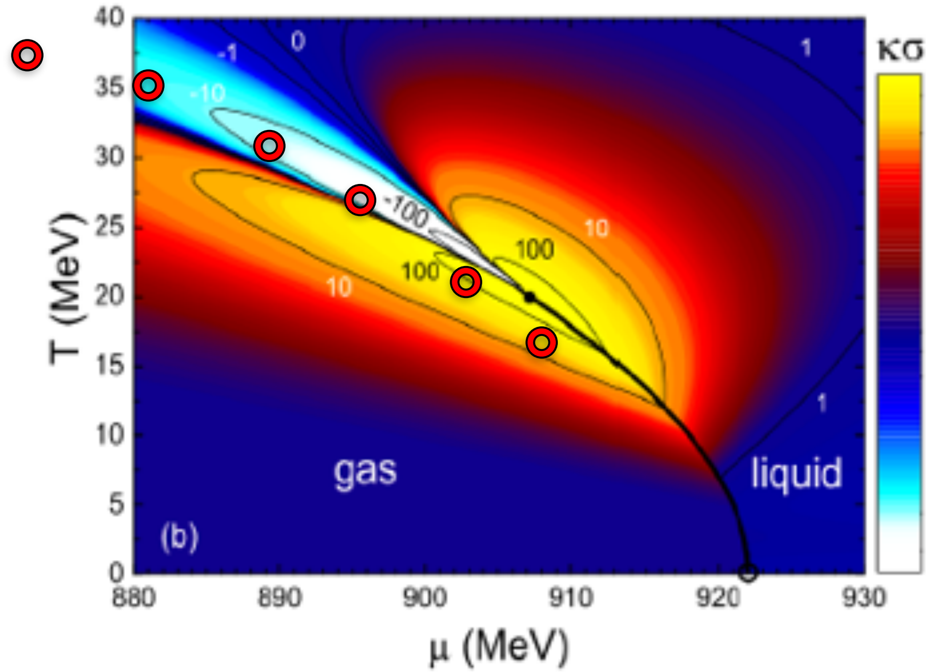


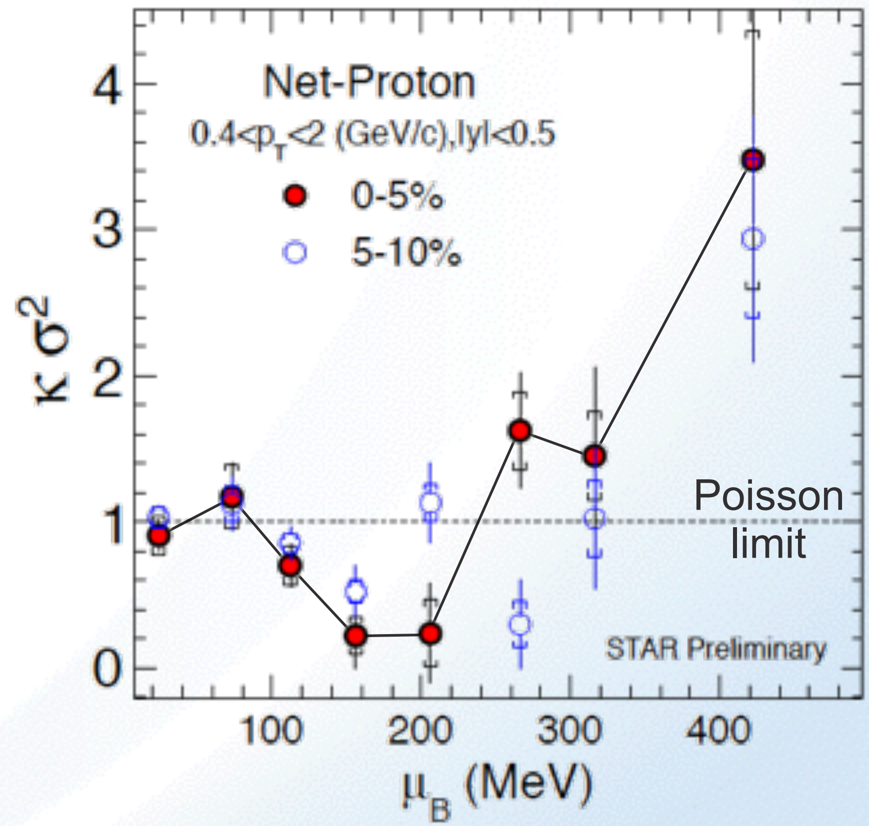


Isobar collisions will determine the fraction of the charge separation due to the CME to within ±6% of the observed signal

BES II: Critical behavior?

The moments of the distributions of conserved charges are related to susceptibilities and are sensitive to critical fluctuations





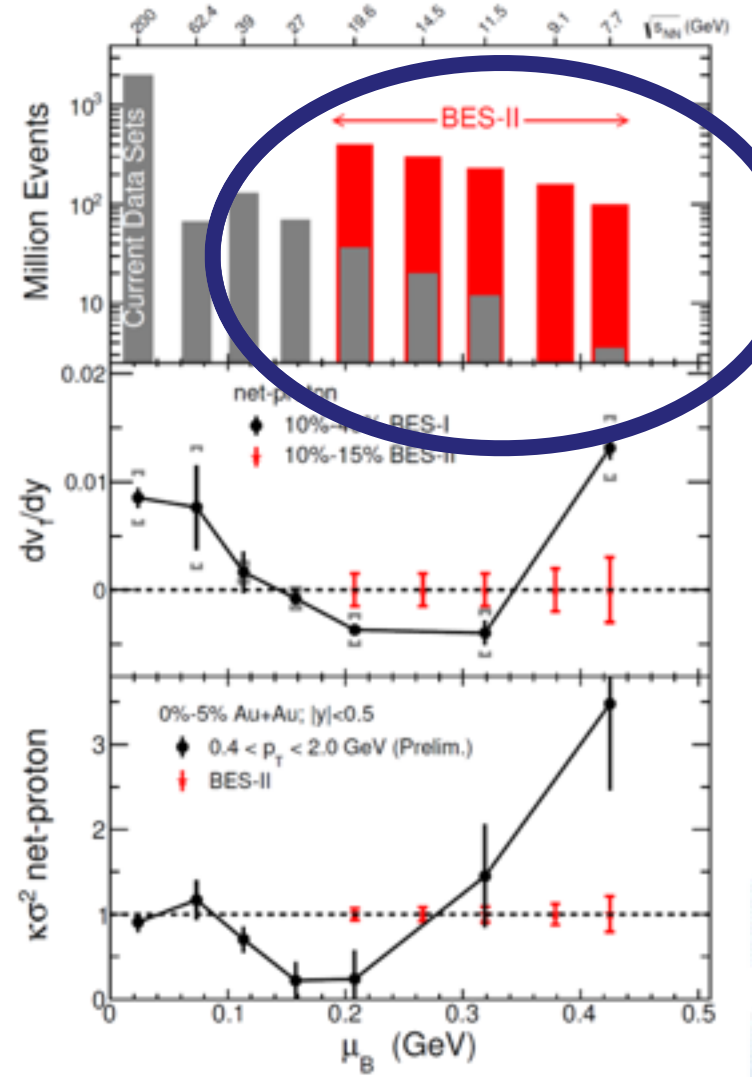
Higher moments like kurtosis*variance $\kappa\sigma^2$-1 change sign near the critical point

Non-monotonic trend observed in BES-I with limited statistical precision!

Beam Energy Scan 2

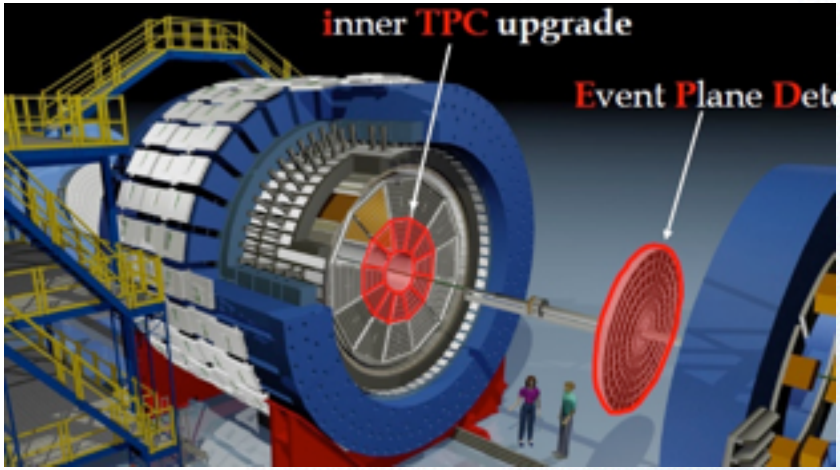
Higher statistics

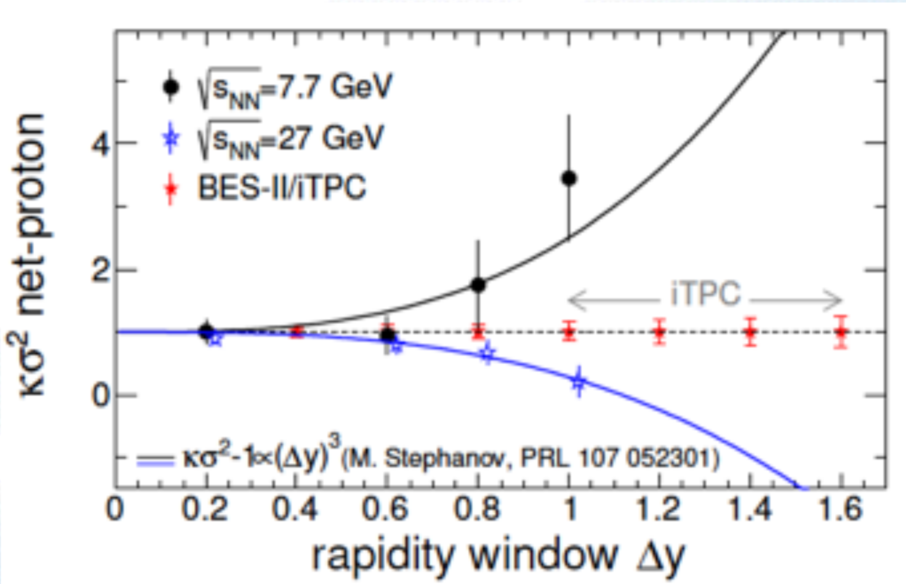
Low energy RHIC electron cooling upgrade



Larger acceptance

STAR iTPC & EPD upgrades

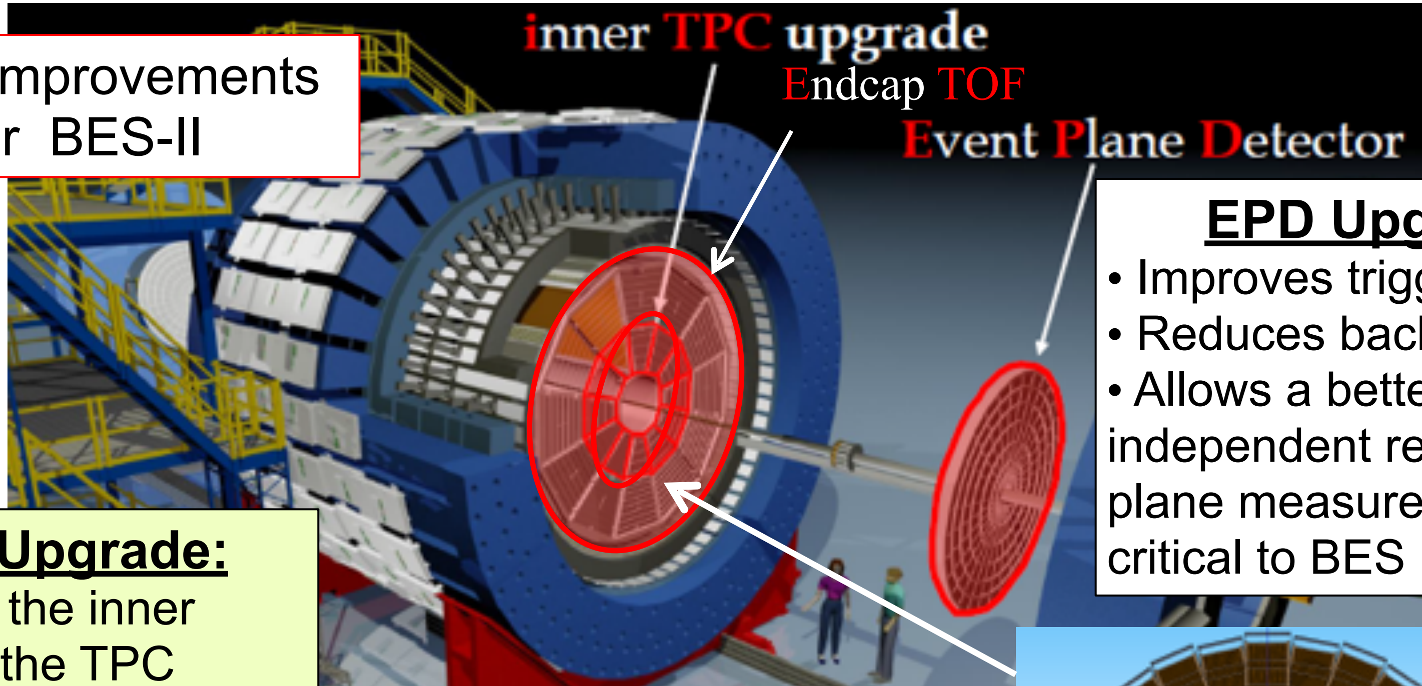




iTPC, LEReC, sPHENIX

STAR Upgrades for BES II

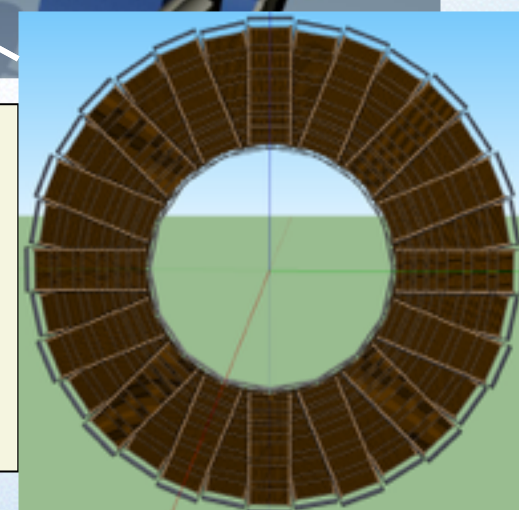
Major improvements for BES-II



EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

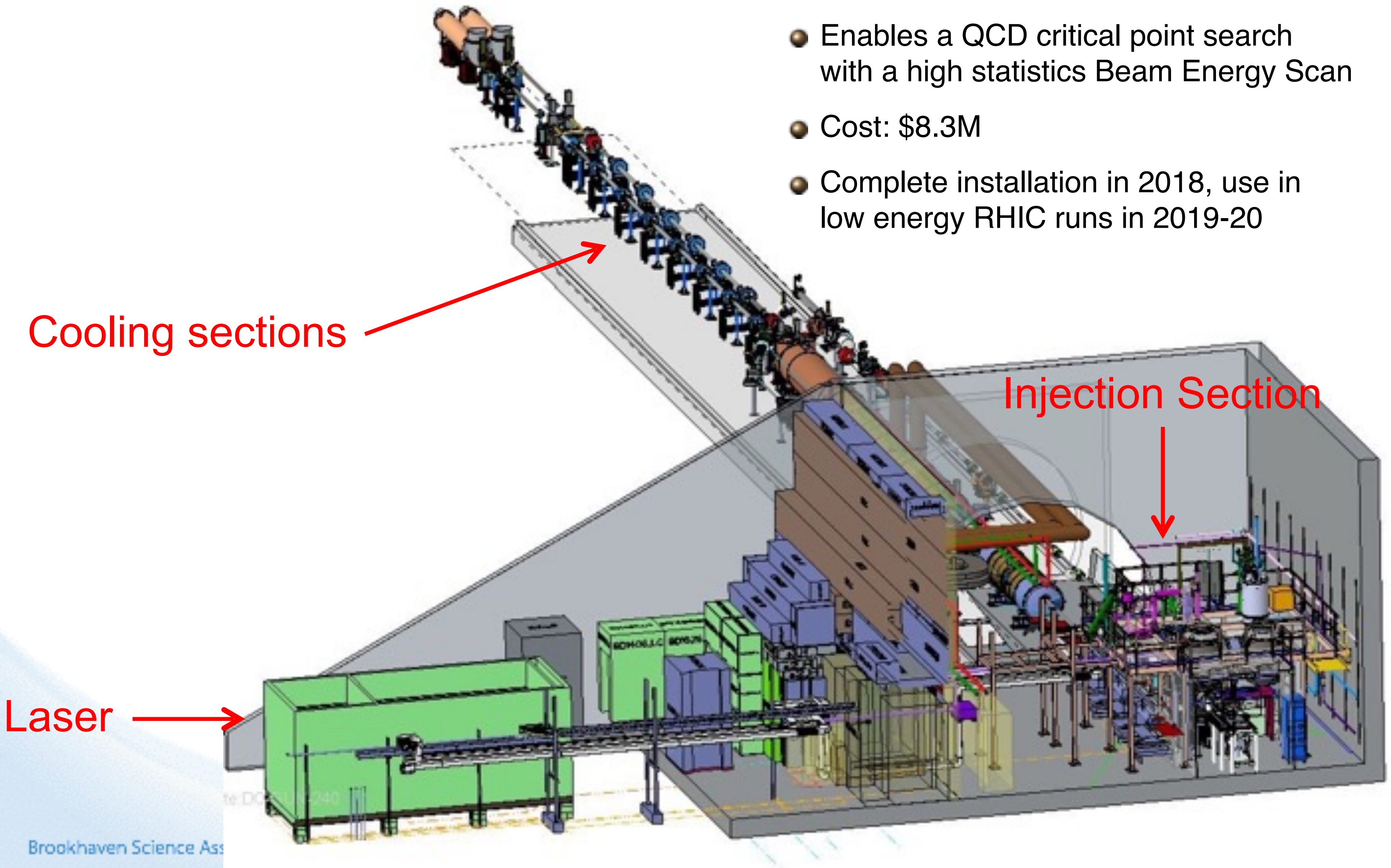
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



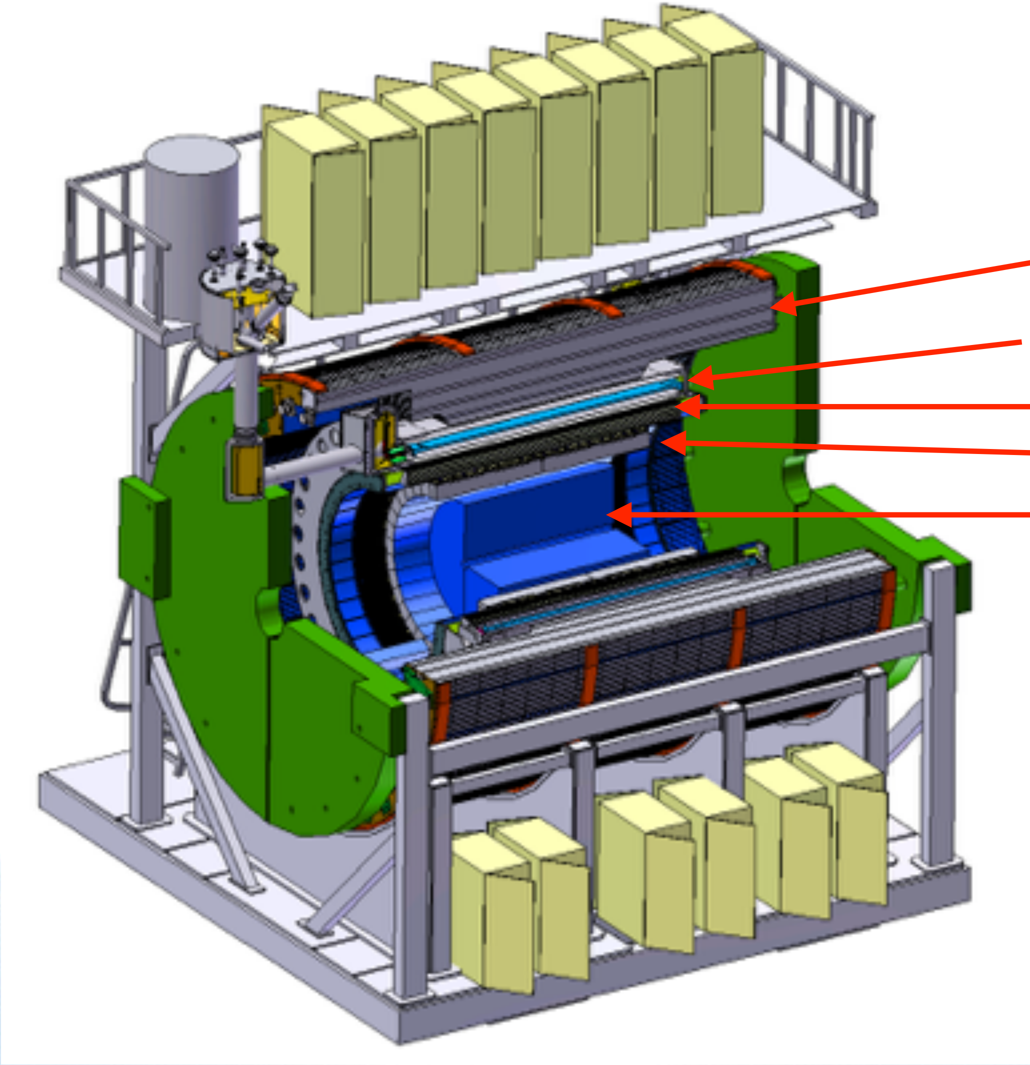
Low Energy e-Cooling for BES-II

- Cooling of low energy heavy ion beams (3.8–5.0 GeV/n) with bunched electron beam to increase luminosity
- Enables a QCD critical point search with a high statistics Beam Energy Scan
- Cost: $8.3M
- Complete installation in 2018, use in low energy RHIC runs in 2019-20



sPHENIX

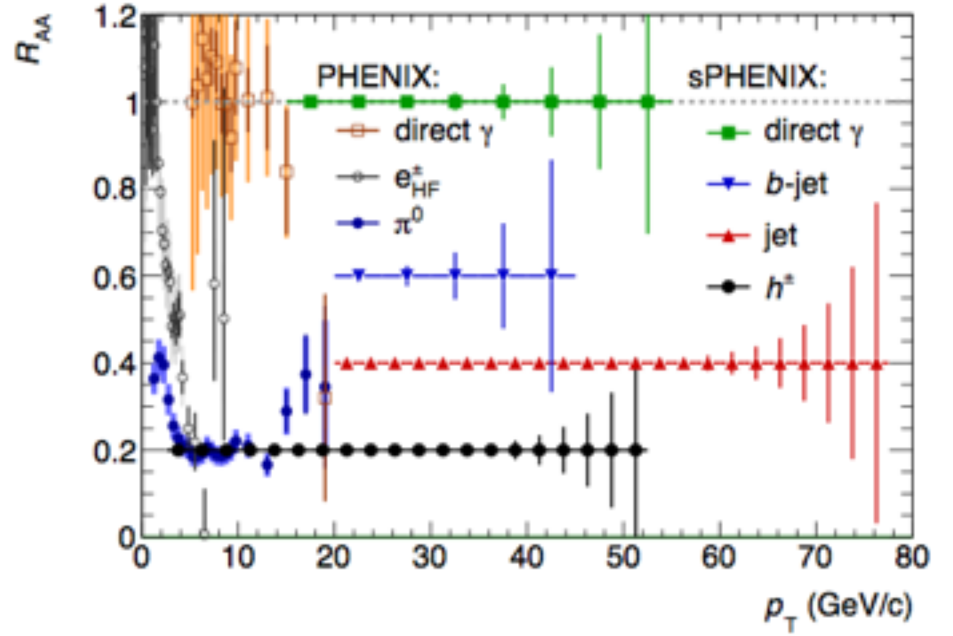
High-rate capable, large acceptance detector built around the former BaBar 1.5T SC solenoid, with full EM and hadronic calorimetry and precision tracking and vertexing,

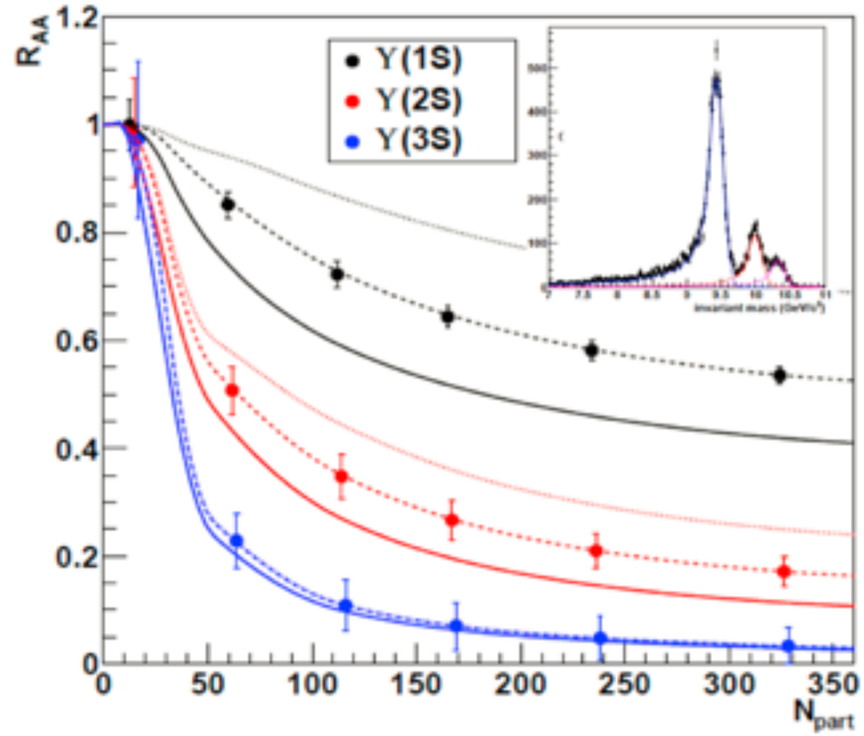


Jets & Upsilon states

sPHENIX capabilities

Complete calorimetric jet spectroscopy



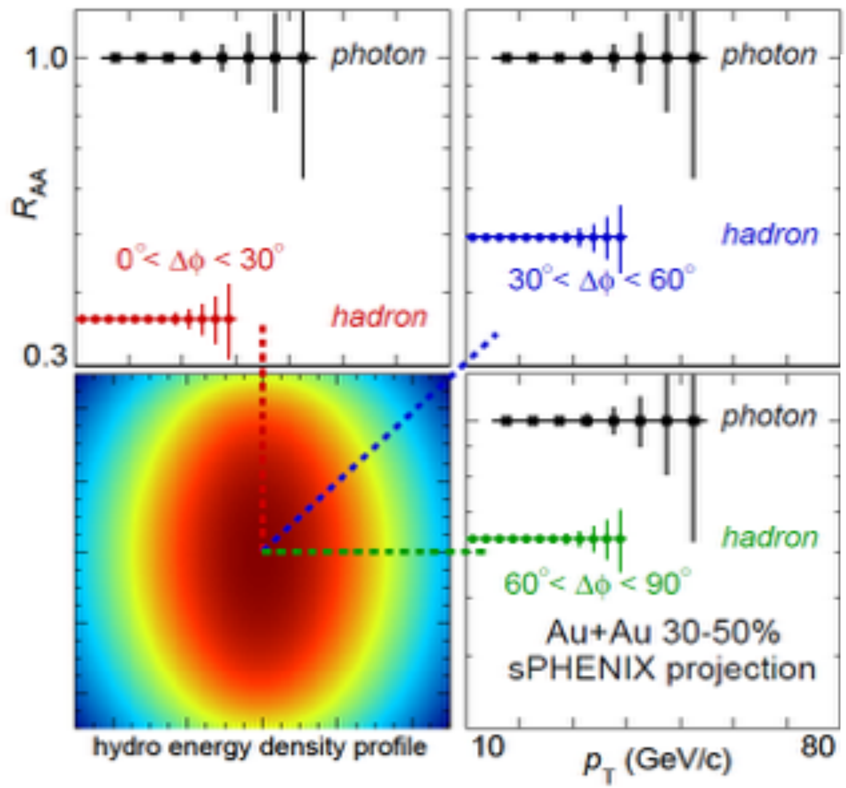


Completely resolved Upsilon spectroscopy

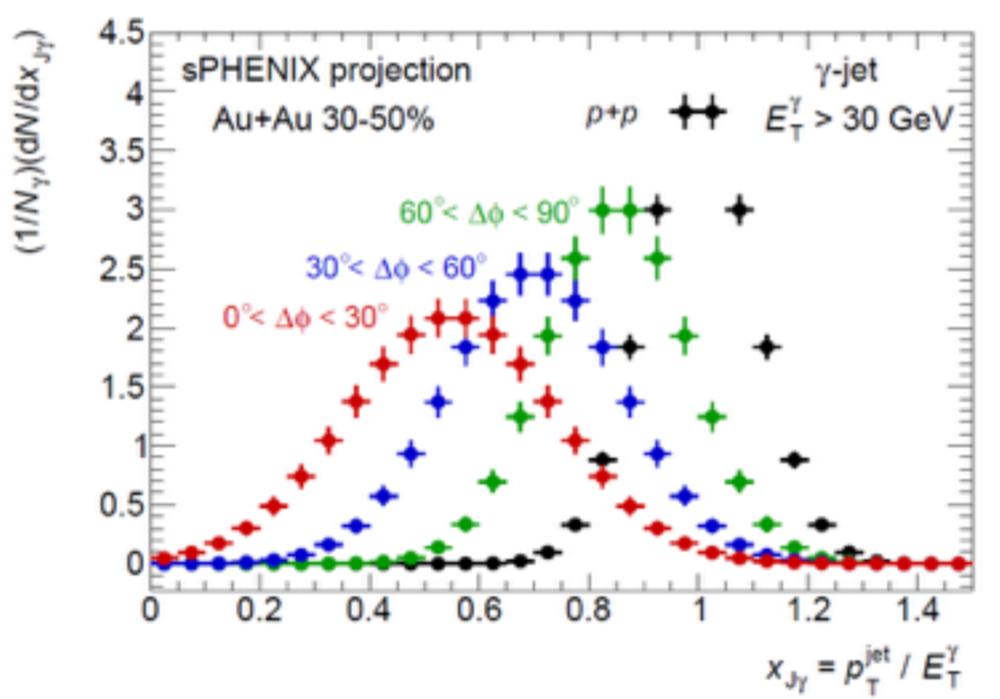
Rate enabled measurements

Example: Length dependent jet quenching

Length dependent suppression R_{AA}



Length dependent energy loss in photon tagged jet events



sPHENIX Status

sPHENIX detector collaboration:

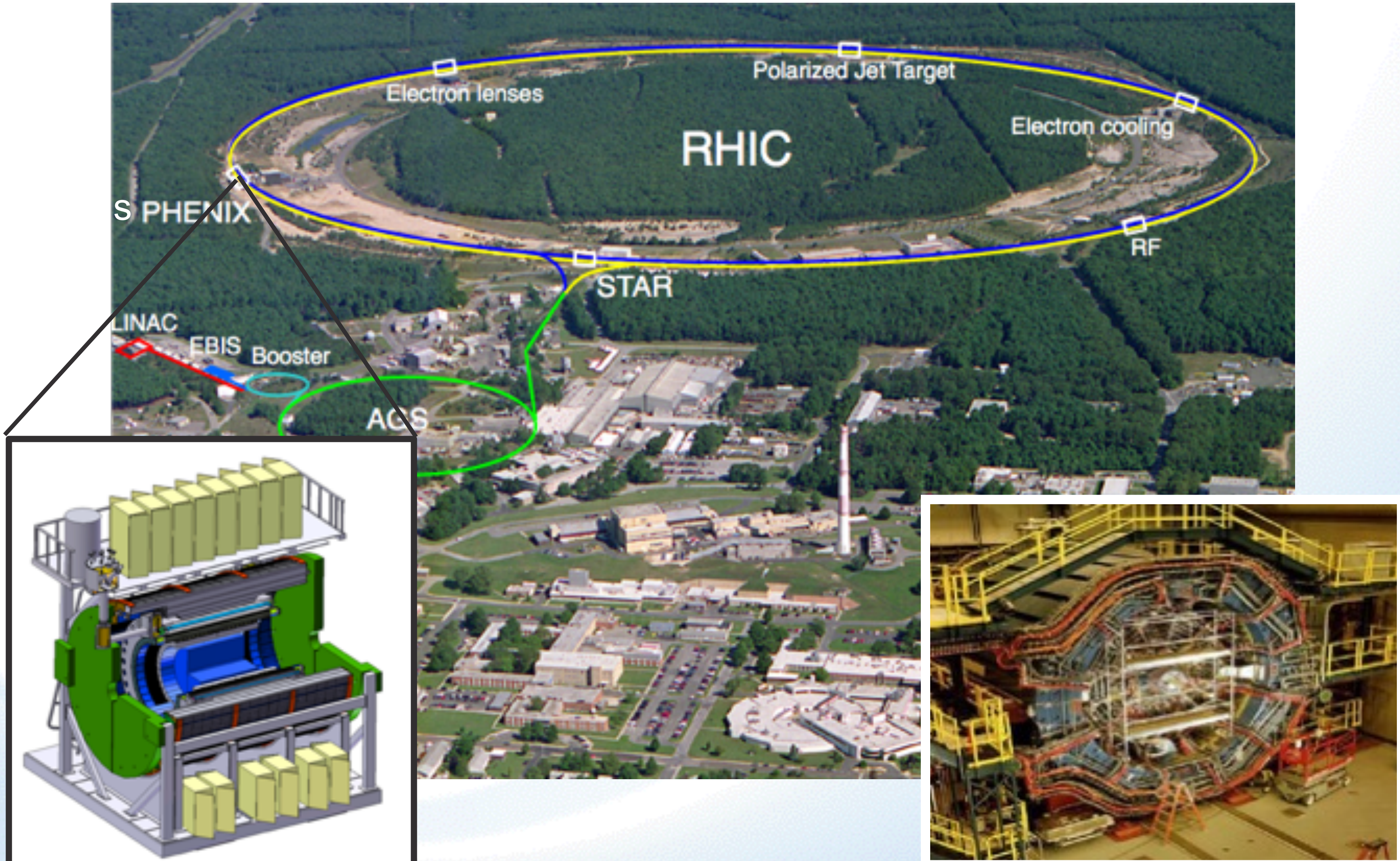
- First collaboration meeting December 2015 at Rutgers
- Collaboration spokesperson team (Roland/Morrison) elected
- Second collaboration meeting May 2016 at BNL

sPHENIX Project progress:

- Science case recommended in new NSAC LRP
- Successful science review by DOE April 30, 2015
- PMG advising ALD meets bi-weekly
- Preliminary CDR completed
- Director's cost and schedule review November 2015
- Removal and Repurposing of unneeded PHENIX components started
- Re-scoping exercise by Collaboration completed
- Tracker review scheduled for early September 2016
- Detailed reports by G. Roland and E. O'Brien

Long term vision

The RHIC Facility in 2022



Proposed run schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2016	High statistics Au+Au d+Au beam energy scan	Complete heavy flavor program First measurement of Λ_c Collectivity in small systems	Coherent e-cooling test I
2017	High statistics Pol. p+p at 510 GeV	Transverse spin physics	Coherent e-cooling test II
2018	^{96}Zr+^{96}Ru at 200 GeV Au+Au at 27 GeV ?	Establish chiral magnetic effect	Low energy e-cooling upgrade
2019-20	7.7-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR iTPC upgrade EPD upgrade
2021	TBD	Contingency for BES-2 extension ?	sPHENIX installation
2022-??	200 GeV Au+Au with upgraded detectors Pol. p+p, p+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX Forward upgrades ?
mid-2020s	Transition to eRHIC ?	Gluon structure of p and A	Upgrade to “ePHENIX” ?

What RHIC will deliver

What RHIC will deliver

- **Campaign 1 (2014-17):**
  - **QCD equation of state at $\mu_B \approx 0$**
  - **Precision measurement of $\eta/s(T \approx T_c)$**
  - **Measurement of heavy quark diffusion constant $D_{c/b}$**
  - **Measurement of nucleon/nuclear granularity at small x**
  - **Δg, flavor dependence of spin in the quark sea**
  - **Origin of single spin asymmetries**

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  - **Measurement of nucleon/nuclear granularity at small x**
  - **Δg, flavor dependence of spin in the quark sea**
  - **Origin of single spin asymmetries**
- **Campaign 2 (2018-20):**
  - **QCD equation of state at $\mu_B > 0$**
  - **Discovery of the QCD critical point, if within range**
  - **Discovery of QCD anomaly driven transport in chiral QGP**

What RHIC will deliver

- **Campaign 1 (2014-17):**
  - QCD equation of state at $\mu_B \approx 0$
  - Precision measurement of $\eta/s(T \approx T_c)$
  - Measurement of heavy quark diffusion constant $D_{c/b}$
  - Measurement of nucleon/nuclear granularity at small x
  - Δg, flavor dependence of spin in the quark sea
  - Origin of single spin asymmetries
- **Campaign 2 (2018-20):**
  - QCD equation of state at $\mu_B > 0$
  - Discovery of the QCD critical point, if within range
  - Discovery of QCD anomaly driven transport in chiral QGP
- **Campaign 3 (2022-??):**
  - Precision measurement of $\hat{q}(T \approx T_c)$ and $\hat{e}(T \approx T_c)$
  - Length scale where the QGP becomes a liquid
  - Additional insights we can't even anticipate yet

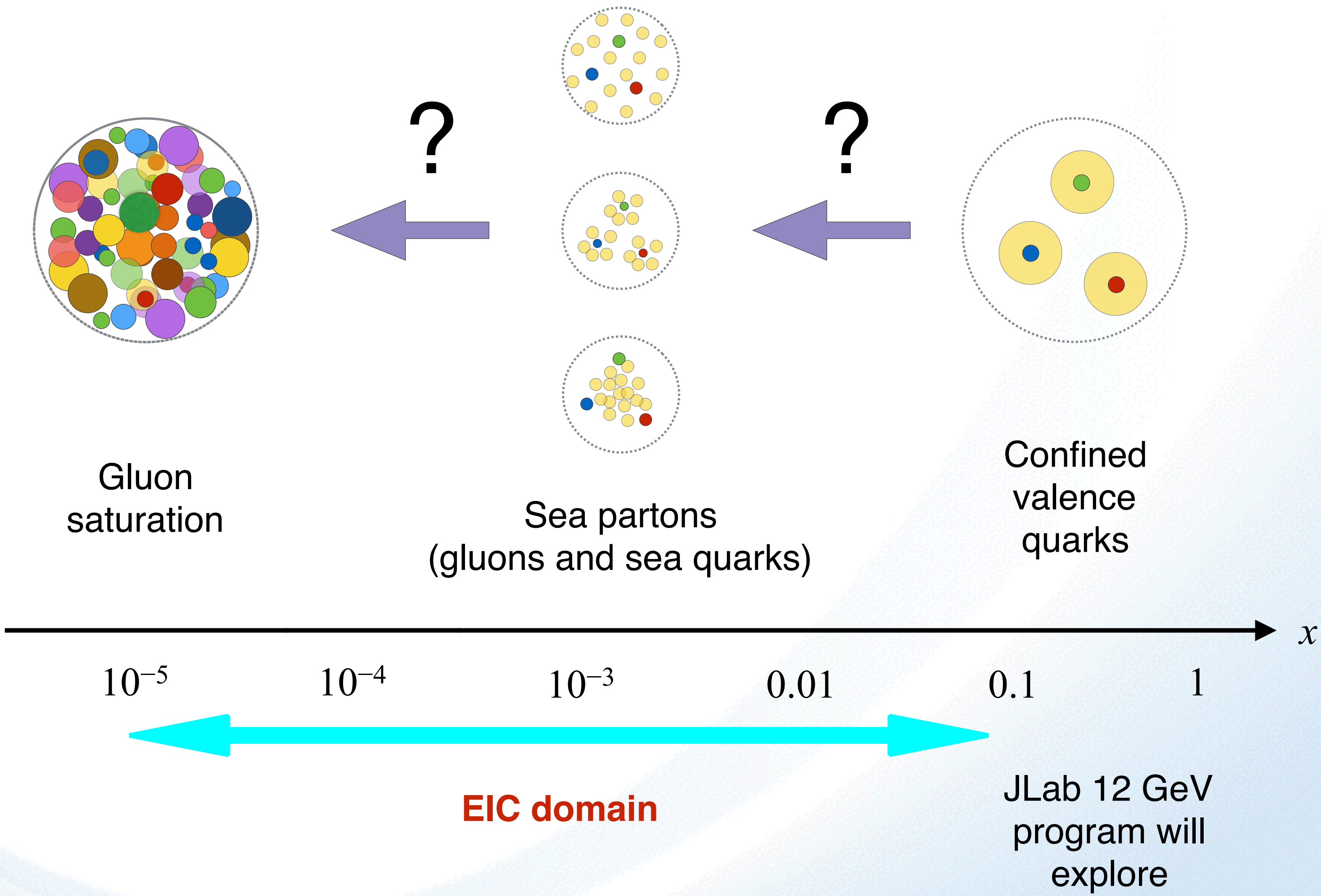
2015 NSAC Long Range Plan

RECOMMENDATION III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

Parton structure of the proton



eRHIC Concept

The eRHIC concept exploits the RHIC Heavy Ion collider complex by **adding an electron accelerator** that

- makes use of superconducting LINAC technology and recirculation
- utilizes **either** the energy recovery concept
- **or** a high intensity electron storage ring
- to achieve **high luminosity electron-hadron collisions**

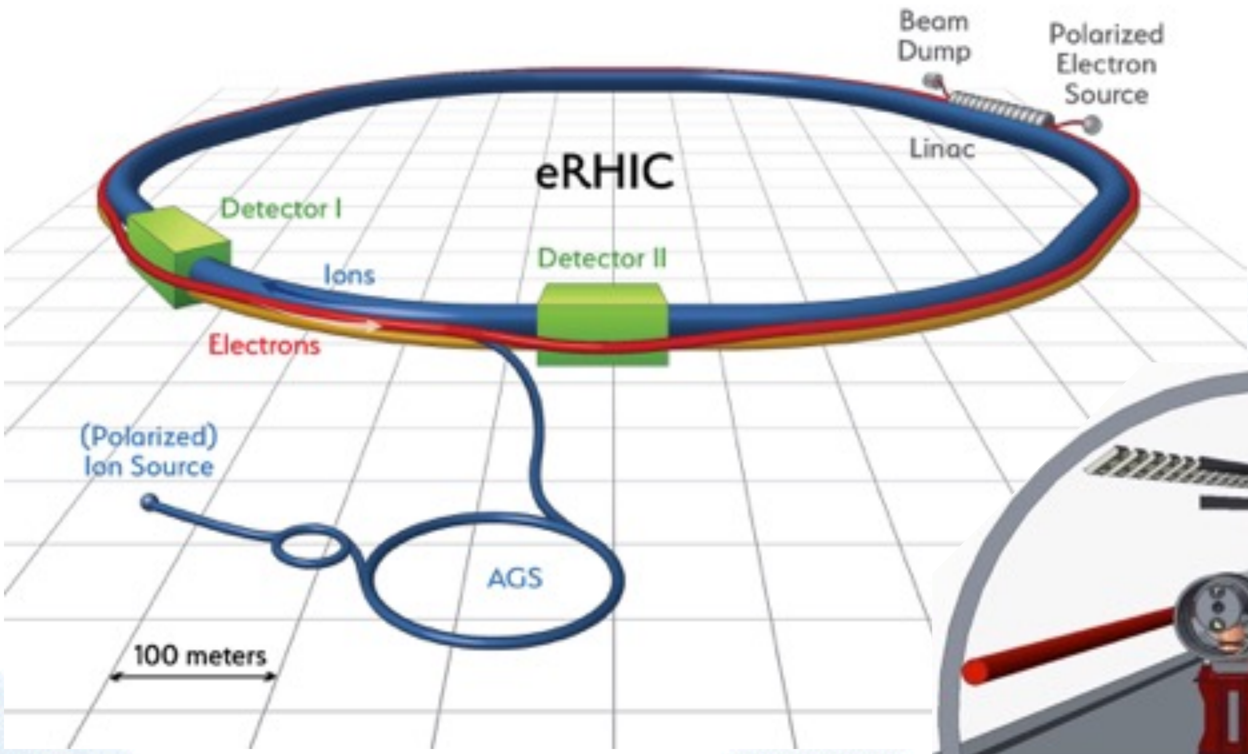
A design meeting **all** the requirements of the physics program described in the EIC White Paper delivering luminosities of **$>10^{33}s^{-1}cm^{-2}$** over the entire range of CM energies with a maximum luminosity in excess of **$10^{34}s^{-1}cm^{-2}$** was worked out in 2014.

However, we realize that this design is based on novel technologies that require a long term R&D program and demonstration of feasibility before a commitment can be made to build a large facility based on this approach.

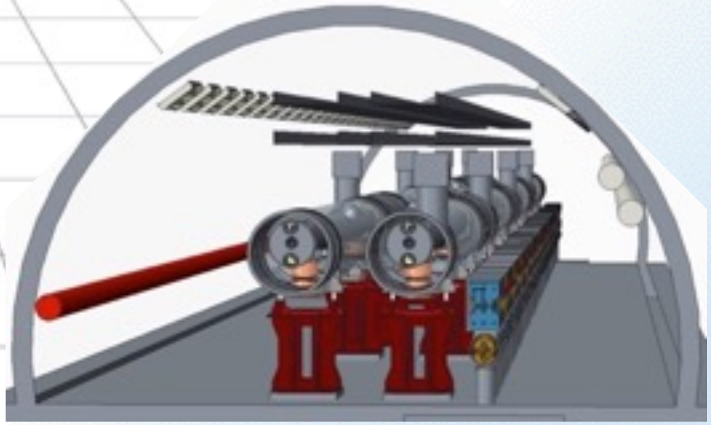
BNL EIC Design: eRHIC

eRHIC ERL + FFAG ring design @ 10^{33}–10^{34}/cm^{2}s

~20 GeV e^- + 255 GeV p or 100 GeV/u Au.



Day-1 Detector



eRHIC Strategy

⇒ Design a eRHIC start version towards lower luminosity 10^{32}–10^{33} $s^{-1}cm^{-2}$ that enables a compelling initial science program

This lower boundary condition makes a **storage ring** based collider an interesting alternative to a **multi-pass ERL** based concept.

→ Strategy towards eRHIC Design:

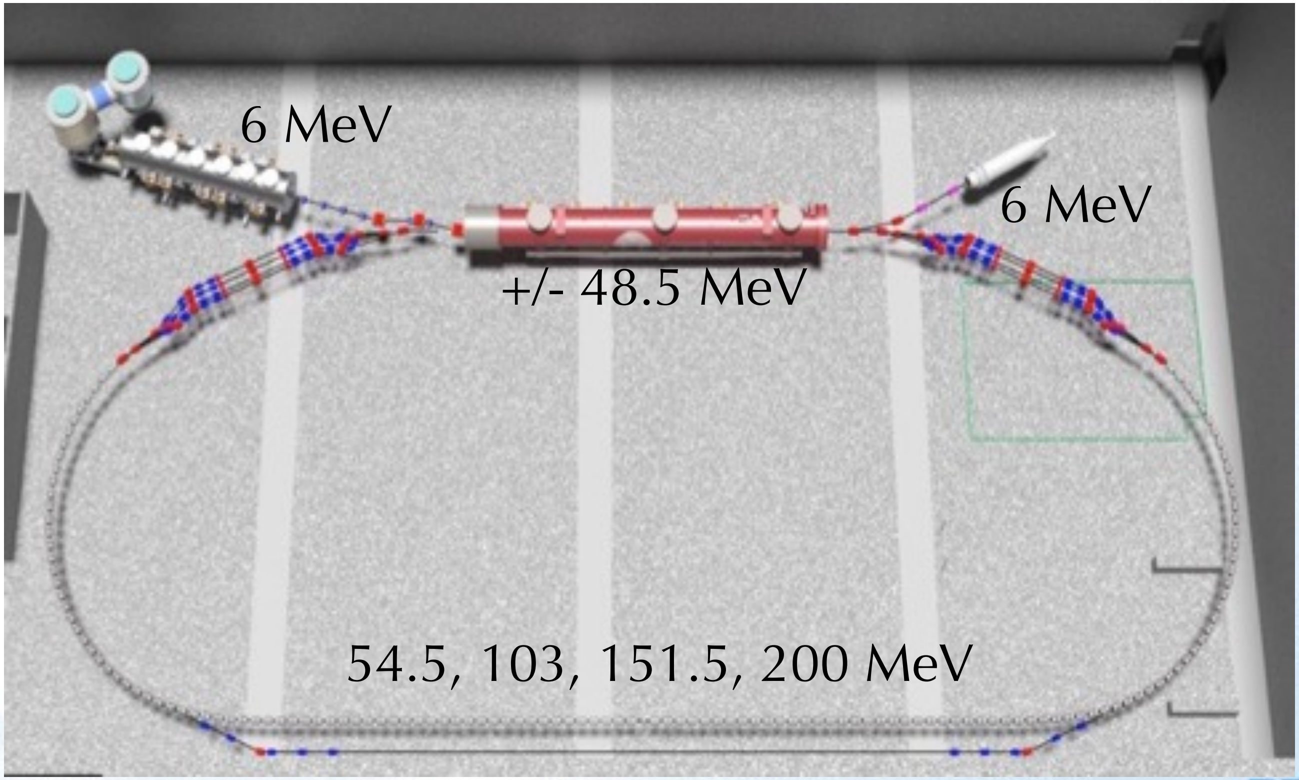
- Study in parallel multi-turn ERL and storage ring based collider designs
- Compare the two options in terms of performance, residual risk and cost, and feasibility of high luminosity upgrade
- Select a final conceptual design for the eRHIC start version in the near future

Key Elements of the ongoing long term R&D program are:

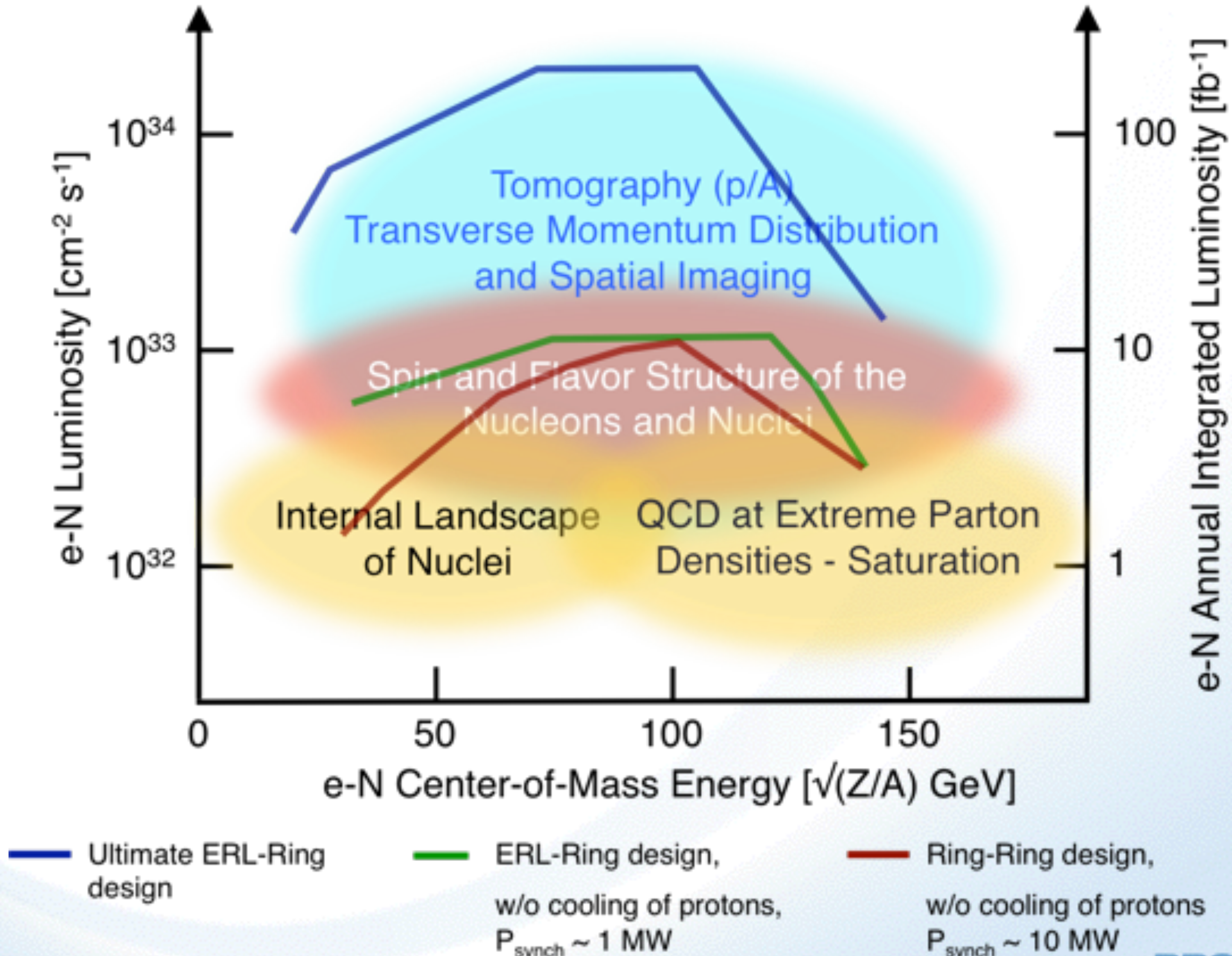
- High-rate electron cooling (CeC proof-of principle expt)
- High average current polarized electron
- Multi-pass superconducting energy recovery LINAC
- FFAG-based recirculation scheme could be a significant cost saver

C-Beta: Multi-pass Test-ERL at Cornell

- Uses existing high-current injector and 48.5 MeV CW SRF Linac
- ERL with single four-pass recirculation arc using permanent magnets
- NY State funding ($25M) awaits September NYSERDA board meeting
- Cost/schedule review scheduled for October 2016



Physics vs. Luminosity & Energy



Laboratory Support Synergies

Lab/other investments

- LDRD/PD support for NPP increased from \$2.3M (FY14) to \$8.8M (FY16)
- Total LDRD/PD support for RHIC/eRHIC: \$4.5M (FY16)
- Lab support for postdocs in NPP: ~\$500k (FY16)
- \$500k/year Lab support for RIKEN-BNL Research Center
- Chinese investments in STAR (iTPC upgrade, High Level Trigger, EPD)
- STAR TOF from CBM @ FAIR
- NY State support (\$25M) for multi-pass ERL prototype (C-Beta) in collaboration with Cornell close to final approval
- Institutional compute cluster (NY State support)

Synergies

- Japanese support for **R**IKEN-**B**NL **R**esearch **C**enter: ~$4M/year
- Joint appointments with SBU:
  - D. Kharzeev, J. Jia, V. Litvinenko (50/50)
  - Many non-salaried joint appointments (Brookhaven Prof., adjunct, etc.)
  - JA with U. Bielefeld (Karsch)
- **B**rookhaven **L**inear **I**sotope **P**roducer (medical isotopes)
- **N**ASA **S**pace **R**adiation **L**aboratory (NASA funded)
- **A**ccelerator **T**est **F**acility (HEP accelerator stewardship)
- **C**enter for **A**ccelerator **S**cience and **E**ducation (SBU)
- Lattice gauge theory (HEP)
- **R**HIC-**A**TLAS **C**omputing **F**acility (HEP)
- BNL **C**omputational **S**cience **I**nitiative (ASCR, NY State)

Recent actions
Previous Recommendations

Recent actions & issues

- Eric Lançon new RACF Director (succeeds M. Ernst)
- Bill Christie new head of experimental operations in C-AD
- Ferdinand Willeke new Director of eRHIC R&D
- Thomas Roser now also Deputy ALD for Accelerators
- Jianwei Qiu new Nuclear Theory Group Leader
- Larry McLerran leaves BNL to become INT Director
- Offer to Zhongbo Kang (LANL - 50% RBRC) outstanding
- RHIC experimental staff adjustment to match funding
- CSWP site visits to RHIC collaborations
- Task Force on STAR computing (PAC recommendation)

DOE Recommendations 2014

- ✔ Evaluate in detail the performance of the HFT, with respect to luminosity-related degradation and establish a detailed plan of operation for run 15 and beyond. Report progress at the DOE HFT quarterly status meetings. DONE
- ✔ Prepare a report on detector data collection efficiency, estimating or measuring the contributions to the efficiency reduction. The report should report the expected limit of the average efficiency and the five most important contributors to the efficiency. This report should be submitted to DOE by January 12, 2015. Report included.
- ✔ BNL is encouraged to resolve the HVAC problem at RACF as soon as possible. Updates on plans and progress should be provided quarterly in regularly scheduled bi-weekly phone conferences with the Office of Nuclear Physics. DONE
- ✔ The RACF and the detector collaborations should analyze the processing capacity required to perform the necessary production runs (in units of HS06*years) and compare to the available capacity of RACF. If additional capacity is required, a plan to acquire the necessary capacity by 2018 should be developed. This plan should be submitted to DOE by January 12, 2015. Report included. Problem continues because RHIC data volume growth exceeds computing power growth.

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- **RHIC enabled R&D to retire major risks of ultimate EIC design (CeC, c-BETA, SRF, e-gun)**